AD NUMBER

ADB146160

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; 13 Jul 1990. Other requests shall be referred to DARPA/TIO, 1400 Wilson Blvd., Arlington, VA 22209.

AUTHORITY

Defense Advanced Research Projects Agency ltr., dtd June 11, 2001.

2

R-6280

ASSESSMENT OF ULTRA-WIDEBAND (UWB) TECHNOLOGY

Prepared by

OSD/DARPA Ultra-Wideband Radar Review Panel

BATTELLE
Tactical Technology Center
505 King Avenue
Columbus, Ohio 43201-2693

Under

Contract No. DAAH01-88-C-0131
ARPA Order 6049

July 13, 1990

CRITICAL TECHNOLOGY

Distribution ~~limited to~~ U.S. Government agencies and their contractors; ~~Test and Evaluation~~ (July 13, 1990). Other requests for this document shall be referred to DARPA/TIO, 1400 Wilson Blvd, Arlington, VA 22209.

Sponsored by

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
Arlington, Virginia 22209-2308

Monitored by

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35898-5244

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 13, 1990	Final

4. TITLE AND SUBTITLE
ASSESSMENT OF ULTRA-WIDEBAND (UWB) TECHNOLOGY

5. FUNDING NUMBERS
Contract No.
DAAH01-88-C-0131,
ARPA ORder No. 6049

6. AUTHOR(S)
OSD/DARPA Ultra-Wideband Radar Review Panel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Battelle
Tactical Technology Center
Columbus, Ohio 43201-2693

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Advanced Research Projects Agency
Arlington Virginia 22209-2308

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

CRITICAL TECHNOLOGY

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution ~~limited~~ Auth to U.S. Government agencies and their contractors; ~~Test and Evaluation~~ (July 13, 1990). Other requests for this document shall be referred to DARPA/TIO, 1400 Wilson Blvd., Arlington, VA 22209.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The Defense Advanced Research Projects Agency (DARPA) and the Office of the Secretary of Defense (OSD) tasked Battelle to review ultra-wideband (UWB) technologies and applications. Battelle convened the Ultra-Wideband Radar Review Panel ~~to~~ examine the state of the art and the potential performance benefits and limitations of UWB technology, with particular emphasis on radar applications. The Panel was tasked with identifying and prioritizing UWB research to be pursued and exploited. This report presents the Panel's findings.

14. SUBJECT TERMS
Radar, Wideband, Impulse Radar
RF, Ultra-wideband

15. NUMBER OF PAGES
221

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

INTENTIONALLY LEFT BLANK

FOREWORD

The Defense Advanced Research Projects Agency (DARPA) and the Office of the Secretary of Defense (OSD) tasked Battelle to review ultra-wideband (UWB) technologies and applications. Battelle convened the Ultra-Wideband Radar Review Panel to examine the state of the art and the potential performance benefits and limitations of UWB technology, with particular emphasis on radar applications. The Panel was tasked with identifying and prioritizing UWB research to be pursued and exploited. This report presents the Panel's findings.

DISCLAIMER

The views and conclusions contained in this document are those of the OSD/DARPA Ultra-Wideband Review Panel and should not necessarily be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government, or the views or policies of Battelle.

INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Introduction

In view of the interest in ultra-wideband (UWB) technology, the Defense Advanced Research Projects Agency (DARPA) and the Office of the Secretary of Defense (OSD) contracted with Battelle to assess UWB technology and its potential military applications. Battelle convened a panel of experts drawn from the various technical areas concerned with UWB technology in order to perform this assessment. The Panel's assignment was to review the status of the work in the field, to examine the validity of a number of claims made by proponents, to determine potential performance benefits, and to recommend areas for Government R&D support. The Terms of Reference are given in Appendix A, along with a list of Panel members, Government advisors, and presenters, and the agendas of the Panel meetings.

The Panel reviewed available experimental data, analyses, literature, and various studies. It examined past and proposed research at DoD and DOE laboratories, as well as by industry and academia. It invited the proponents of UWB technology to disclose and explain their approaches, methods, and recommendations. It gave consideration to all views, and worked to identify and prioritize promising concepts for exploitation of UWB phenomena. This report presents the results of these efforts and recommends research which the Panel believes should be pursued and identifies areas which the Panel believes are not worthy of pursuit.

Scope

Interest in UWB technology has focused on three areas:

- Radar
- Communications
- Electronic warfare (EW) and RF weaponization.

The Panel concentrated on radar but invited the presentation of ideas on communications. No ideas or proposals for UWB communications systems or techniques were presented, nor were any advantages for such systems apparent to the Panel. Examination of electronic warfare and RF weaponization applications was very limited. The restrictions imposed by the combination of security classification and the proprietary nature of many of the EW and weaponization concepts under development by the presenters made it difficult for the Panel to conduct an in-depth review of these areas. Further, the DoD has established a separate in-house committee to review a broader area that includes UWB applications to electronic warfare and weaponization. Thus, the Panel's efforts were almost entirely devoted to UWB radar issues.

Features of UWB Radar

UWB radars are characterized by very wide bandwidths and the commensurate fine range resolution. There are applications in which range resolutions on the order of one foot are desired, such as imaging typical tactical targets, and wideband techniques are routinely used for these. However, there are associated disadvantages as well, as evidenced by the preference to use the narrowest bandwidth consistent with need in order to minimize the processing burden. For example, a tenfold increase in bandwidth has significant impact on the cost of a system since, for a given surveillance volume, the number of resolution cells to be processed and the required processing for detection are both proportional to the bandwidth. In addition, the tenfold increase in number of cells, for all else constant, implies about a tenfold increase in the probability of false alarm or a small decrease in system sensitivity. For these reasons, wideband or ultra-wideband are used only when the increased percentage bandwidth presents a distinct advantage.

Essentially all of the interest in (and claims for) UWB radars have related to an impulse radar implementation which, in its simplest form, generates its radiated energy by applying a very short video pulse (hence "impulse") to an antenna. Other forms of UWB radars, "non-impulse" radars, are generally extrapolations and extensions of so-called conventional radars. Consequently, the Panel's efforts were concentrated on impulse radar technologies and capabilities.

Discussion

Impulse radars have been around for a long time and there are a number of fielded systems that have been successfully used for terrain profiling and ground penetration to find buried objects.

The recent general interest, however, has centered on claims involving counter-stealth capabilities, Low Probability of Intercept (LPI), and detection of relocatable targets (in camouflage and foliage). In the technical community, there has been controversy over assertions that the "standard" analytical tools were either inappropriate or inadequate to deal with impulse radar issues.

An impulse radar can have substantial low frequency content and typically has high peak power and short pulse length. These properties are the basis for claims of unusual capabilities. In examining the subject, the Panel found it useful to separate such claimed capabilities into two categories: (1) those involving *phenomena which are unique* to impulse radars and (2) those in which impulse radar may offer one or more *advantages in implementation*.

Most of the claims for unique performance capabilities were based upon non-linear effects due to high power and/or short pulses. The Panel found no theoretical or experimental evidence of such effects at frequencies and operating ranges of interest.

The use of self-induced transparency (a truly non-linear phenomenon) has been suggested as a possible method for reducing atmospheric attenuation of millimeter waves. The Panel was able to look into this only briefly. It concluded that the likelihood of achieving a useful military capability taking advantage of potentially reduced atmospheric attenuation was slight but that it would be useful to have someone (e.g., the JASONS, the National Science Foundation, or a university) review and document the whole area of non-linear effects and any possible military applications.

Other claims for unique capabilities were examined and found to be in error. Specifically, "precursors", which have figured prominently in some discussions, are linear transients in distributed media and not unique to impulse systems. Further, the Panel saw no practical radar application of this phenomenon.

There are a number of applications where the combination of high resolution and low frequency is desirable. The most demonstrated are terrain profiling and earth penetration, but others such as foliage penetration or the possibility of simultaneous low-frequency surveillance with high resolution for target identification have been suggested and should be considered. Either conventional wideband (non-impulse) or impulse radars could accomplish these functions, but impulse radars might have a substantive advantage in implementation as measured by cost, size, or weight and deserve detailed examination. Shorter-range applications are most likely to manifest this advantage.

There have been three proposed capabilities for impulse radar that have received wide attention:

(A) Counter-Stealth. The Panel concluded that impulse radar is not "inherently anti-stealth." The primary technique used for achieving low radar cross section is shaping. Low frequencies (HF and VHF) can exploit target resonance effects which are independent of shaping and only a function of size. This phenomenon, however, holds for any radar operating in those bands and impulse radars have no unique advantages against shaping.

There are no effects in radar absorbing material (RAM) that are unique to impulse radar. Field strengths in practical applications are too low to excite material non-linearities. All observed effects are due to "out-of-band" operation (with respect to the RAM) and predictions to the contrary are due to a misunderstanding of electromagnetics. Standard measurement and diagnostic techniques routinely used by the stealth community deal with these issues completely.

(B) Detectability of the Radar (LPI). To make a radar's signal more difficult to intercept, radar designers resort to the use of complex waveforms and large processing gains. Even so, it is difficult to make a radar hard to detect even in the sidelobe region. The Panel concluded that the impulse radar, which typically has less processing gain, has no special LPI characteristics and is readily detectable by an appropriately designed intercept receiver.

(C) Detection of Relocatable Targets. A capability of interest to both strategic and tactical forces is the detection of military targets when shielded or obscured by trees. Consequently, there has been interest in developing a foliage-penetration imaging radar with sufficient resolution to detect targets of interest with an acceptable false alarm rate. A radar with a resolution on the order of a few feet and operating at frequencies low enough to have tolerable attenuation through foliage might provide a useful capability. The Panel suggests that an impulse radar with a center frequency of a few hundred Megahertz may well be the best way to implement such a system. These design efforts and, if appropriate, experiments are needed to establish the military utility of such a system.

The Panel reviewed and analyzed all the other areas and issues pertinent to impulse radar. The Panel was favorably impressed by the designs of the existing systems for terrain profiling, etc.; by the possibilities of other short-range and possible medium range radar applications (See Recommendation A-1); and with the work on "sources" (i.e., generators of very high power pulses) and their possible application to conventional as well as impulse transmitters. Other than these issues, nothing startling or of unusual merit was found for impulse radar.

The Panel also reviewed the claim that conventional analysis techniques were not applicable to impulse radar, and found that this claim was due to inadequate understanding of the issues or erroneous application of electromagnetic theory and is incorrect.

Principal Conclusions

(A) The Panel concluded that there is no credible evidence of unique phenomenological capabilities related to the claims made or proposals advocated to the Panel.

(B) The Panel concluded that impulse radar is not "inherently anti-stealth."

(C) The Panel concluded that impulse radar has no special LPI characteristics and is readily detectable by an appropriately designed intercept receiver.

(D) The Panel concluded that all applications presented could be implemented by alternative "non-impulse" techniques.

For every application of impulse radar which was presented, a corresponding example using a non-impulse radar was found. The Panel saw no applications for which only an impulse radar could work.

(E) The Panel found that impressive accomplishments have been achieved on impulse radars for terrain profiling, ground probing, and diagnostics--all short-range applications.

Terrain profiling can be done at higher frequencies, but terrain profiling through foliage requires low frequency and high resolution.

The Panel suggests that impulse radar probably represents the most cost-effective solution for the terrain profiling and ground probing applications.

(F) The Panel found that there may be other applications where impulse radars are preferable to non-impulse approaches due to potentially lower cost and lighter weight.

Impulse radars might have specific advantages for certain applications with regard to size, cost, weight, and ruggedness. Their applicability to other military requirements should be explored. (See Recommendation A-1)

(G) The Panel concluded that the available analysis tools are completely adequate and appropriate for dealing rigorously with impulse radar performance. However, the Panel cautions that care must be given to ensure their correct application and notes that this has not always been the case.

Excluding intensity-driven non-linearities and quantum phenomena, the Panel maintains that conventional classical, linear, time-invariant systems theory, statistical estimation and detection theory, and Maxwell's Equations fully describe all the phenomena presented that relate to impulse and non-sinusoidal radars.

(H) The Panel concluded that advances in sources for generating very high power short pulses are impressive and may be promising for conventional short pulse radar as well as impulse transmitters. These advances do not enable any unique capabilities but may impact the choice among possible implementations to achieve cost or weight advantages.

Key Recommendations

(A) The Panel makes three recommendations for DoD investments in UWB radar related studies and analyses:

(1) In order to examine in detail the implementation trade-off advantages, the Panel recommends that the DoD fund analyses of point designs using impulse and non-impulse approaches for four radar applications which appear to have important military applications:

- A short-range system for detecting moving targets behind walls or foliage
- A short-range airborne imaging radar for detecting military targets under canopy or in wooded terrain
- A medium-range (20 km) air defense radar for detection and non-cooperative identification of airborne targets, including but not limited to helicopters in the tree line
- A medium-range (20 km) radar for detection of sea skimming missiles in fleet defense applications

Suggested performance parameters for each system are given in the text of this report.

The suggested level of effort for each of the point designs is one to two person-years.

(2) In order to support the point design studies in (A)(1) above, the Panel recommends that the DoD fund two other studies relevant to UWB (impulse or non-impulse) system designs:

- A review and analysis (based upon existing theory and measurement data) of clutter behavior for UWB radar systems

- An analysis that characterizes the range and angle pattern of UWB linear and planar antenna arrays.

The suggested level of effort of each study is one person-year.

(3) The Panel recommends that the DoD review the status of UWB source development in order to determine if additional R&D efforts are needed. It is suggested that this review be an in-house effort.

(B) The Panel makes three recommendations against DoD investments in UWB radar related efforts:

(1) The Panel recommends that no measurement programs of any kind on stealth materials or vehicles (e.g., to examine non-linear effects) be funded.

(2) The Panel recommends against funding of any system studies based upon unsubstantiated materials phenomena.

(3) The Panel recommends that no system development be undertaken until the results of recommendations (A)(1) and (A)(2) above are assessed and demonstrate the military value of such system(s).

This is not meant to exclude the investigations in progress at several Government laboratories which are aimed at understanding the technology and implementation implications of UWB radar systems.

(C) Finally, the Panel recommends the DoD sponsor a modest effort to document the characteristics of self induced transparency and any other non-linear effects relevant to their possible contributions to military systems. This work could be accomplished as part of the JASONS' 1990 Summer Study, a National Science Foundation effort, or a funded University effort.

Final Comment

Although, as noted herein, the Panel found interesting work under way and recommends additional efforts, it does not believe impulse radar offers a major new military capability nor correspondingly does it present the threat of a serious technological surprise.

INTENTIONALLY LEFT BLANK

CONTENTS

CONTENTS
(Continued)

TABLES

FIGURES

I. INTRODUCTION

In view of the mounting interest in impulse-related ultra-wideband (UWB) radio frequency technology, the Defense Advanced Research Projects Agency (DARPA) and the Office of the Secretary of Defense (OSD) contracted with Battelle to assess UWB technology and its potential military applications. Battelle convened a panel of experts drawn from the various technical areas concerned with UWB in order to perform this assessment. The Panel's assignment was to review the status of the work in the field, to examine the validity and provide an overall assessment of a number of claims made by proponents, to determine potential performance benefits, and to recommend areas for Government R&D support.

The Panel's duties were to give reasoned consideration to all aspects of UWB technology, to identify both limitations and promising applications for this technology, to assess the operational payoff of these applications, and to recommend research which will confirm the validity of theoretical and operational principles which underlie these phenomena and applications.

Background to This Study

Proponents of UWB technology have advanced various claims and assertions related to its performance advantages over conventional radar technology. For example, it has been contended that special properties of UWB pulses, and their interaction with materials, permit them to negate stealth treatments in a manner not possible with conventional narrowband radars. Even the media have become interested and echoed these contentions. ["In theory, impulse radar escapes absorption by the Stealth's composite coating." (USA Today, October 13, 1989, p. 10A)]. Assertions have been made that UWB radar has special efficacy for detecting sea skimming missiles and even submerged submarines. Some proponents have claimed that UWB technology has a low probability of intercept and is (at the same time) powerful enough to be electromagnetic weaponry.

Congress, too, has participated in creating interest. The restructured Congressionally mandated Balanced Technology Initiative (BTI) had $25 million appropriated to it in the FY90 budget with the specific instruction that these funds be expended only "for a new program in ultrawide bandwidth technology development and light activated high power microwave technologies."

Ultra-Wideband Radar Review Panel Objectives

It was in response to these claims and the Congressional mandate that the UWB Panel was convened for the purpose of examining the state of the art and potential performance benefits and limitations of ultra-wideband technology for radar and countermeasures. The Panel reviewed available experimental data, analyses, literature (including Soviet), and various studies. It examined past and proposed research at DoD and DOE laboratories, by industry and academia. It invited the proponents of UWB technology to disclose and explain their approaches, methods, and recommendations. It gave consideration to all views, and worked to identify and prioritize promising concepts for exploitation of UWB phenomena. This report presents the results of this process, and sets forth recommended research which the Panel believes should be pursued.

The Panel's conclusions are in agreement with and consistent with previous UWB studies performed by ERIM[1] (Environmental Research Institute of Michigan) and by MITRE et al.[2]

Caveats

In view of the variety of applications suggested by proponents of UWB technology, the Panel decided to emphasize radar-related applications of

---

[1]LaHaie, I. J. et al., "An Evaluation of Nonsinusoidal Radar Techniques," ERIM TR-171300-10F, prepared for DARPA/ONR, Contract No. N00014-83-C-0754 (June 1985).

[2]Kramer, J.D.R. et al., "Ultra-Wideband Radar Applicability to Air Defense--Red Team Assessment," MITRE Technical Report M90-18 (March 1990).

impulse UWB technology. The Panel was constrained to respect proprietary and classification issues, and these limitations are to be understood when reviewing this document. Nonetheless, the conclusions and recommendations of the Panel did take into account proprietary and classified information without compromising it. The views expressed in this report represent a concensus of Panel views. The findings and recommendations do not necessarily represent the unanimous views of the Panel members.

II. DEFINITION OF ULTRA-WIDEBAND RADAR

General Bandwidth Considerations

An ultra-wideband (UWB) radar is one that, by implication, has a bandwidth considerably greater than that usually associated with conventional radar systems. However, in order to discuss the subject in some depth, it is necessary to have a more precise definition that is general enough to be useful for all of the many different techniques that are employed to achieve wide bandwidths, yet can be uniquely applied to each specific technique. This requires, first of all, some definition of bandwidth itself - and the literature is replete with many different definitions. For present purposes, however, there are only two definitions needed to distinguish among the various situations. These definitions are discussed here with particular emphasis on their applicability to radar. These definitions must be interpreted liberally, as mathematically precise definitions are difficult to achieve and seldom useful in a practical sense.

Energy Bandwidth, B_E: The energy bandwidth is the frequency range within which some specified fraction, say 90 or 99 percent, of the total signal energy lies. This may be defined for a single pulse, if all pulses are the same, or for a group of pulses that are processed together to yield a single decision. The upper limit of this range is denoted here by f_H and the lower limit by f_L.

Time-Bandwidth Product, TB: The time-bandwidth product of a signal is defined as the product of the energy bandwidth and the effective duration of a single pulse or pulse group. It is a measure of the increase in peak signal-to-noise ratio that can be achieved in the radar receiver by appropriate signal processing.

Ultra-Wideband Radar

In considering ultra-wideband radar, it is customary to relate the energy bandwidth to the center frequency of the band. This is usually expressed as the "fractional bandwidth," which is defined as

$$\text{Fractional Bandwidth} = 2(f_H - f_L)/(f_H + f_L)$$

and may have values ranging from 0 to 2. Some authors prefer to use the term "relative bandwidth," which is just one-half of the fractional bandwidth.

With these preliminaries, the following definition was accepted by the Panel:

> "Ultra-wideband radar is any radar whose fractional bandwidth is greater than 0.25 regardless of the center frequency or the signal time-bandwidth product."

The choice of 0.25 as the defining value is largely arbitrary[1], but does in some sense represent the demarcation between conventional narrowband techniques for implementing radar systems and the need to employ special techniques.

There are many ways in which UWB radars can be implemented. These include the use of linear frequency modulation (FM), stepped FM, pseudorandom phase coding, purely random noise, or short pulses. All methods except the use of short pulses involve the use of signals for which the time-bandwidth product is much greater than unity and, hence, are frequently designated as spread-spectrum techniques.

Impulse Radar

---

[1]There are a number of radar applications discussed in this report. Because the requisite analyses of these applications have not yet been carried out, the *required range resolution* and the *optimum center frequency* (and therefore the percent bandwidth) of a non-impulse type radar solution *are not known*. For this reason, the reader is cautioned to *think* "non-impulse" each time he/she sees the terms conventional, "conventional," or conventional UWB.

Impulse radar is a class of ultra-wideband radar that does not involve spread-spectrum techniques. The Panel assigned the following definition to this type of radar:

> "Impulse radar is an ultra-wideband radar whose signal has a time-bandwidth product on the order of unity."

Alternative definitions of impulse radar have also been suggested, such as "-- a radar whose radiated signal pulse contains no more than four cycles." This definition is consistent with the definition of UWB radar stated above (i.e., fractional bandwidth greater than 0.25). The impulse waveform essentially represents the unconventional approach to achieving ultra-wideband signals. Further comments are made in Appendix B.

Conventional Radar

A conventional radar is, by default, any radar whose fractional bandwidth is less than 0.25. However, this does not imply that UWB radars cannot be achieved with conventional techniques, as pointed out earlier. Conversely, it should be noted that conventional approaches to implementing UWB systems could benefit from the devices being developed for impulse radar (such as UWB antennas). As another example, a long coded pulse having the same frequency coverage as a UWB pulse may well have chips (subpulses) consisting of UWB pulses, and could take advantage of the newer pulse generation techniques.

Range Resolution

The Panel found there to be confusion regarding the relationship between ultra-high range resolution and UWB radar. Range resolution depends only upon the absolute value of the energy bandwidth and not upon the portion of the frequency spectrum in which this bandwidth exists. Thus, a radar having an energy bandwidth of 3 GHz centered at 55 GHz has a 5-cm range resolution but is not ultra-wideband in terms of the Panel's definition. The 3-GHz bandwidth centered at 10 GHz is ultra-wideband but has exactly the same range resolution. The distinctive characteristic of UWB signals is the combination of a wide absolute bandwidth with a lower center frequency. The phenomenology associated with these signals (such as ground or sea clutter characteristics) has not been fully explored yet.

III. FEATURES OF UWB RADAR

UWB radars are characterized by very wide fractional bandwidths and the commensurate range resolution. There are applications in which range resolutions on the order of one foot or less are desired, such as imaging typical tactical targets, and wideband techniques are routinely used for these. However, there are disadvantages as well, and surveillance radar designs generally use the most narrow bandwidth consistent with the needs in order to minimize the processing. For example, for a given surveillance volume, the number of resolution cells to be processed and the required processing for detection is proportional to the bandwidth, and a tenfold increase has significant impact on the cost of the system. In addition, the tenfold increase in number of cells, with all else constant, implies about a tenfold increase in the probability of a false alarm as well. For these reasons, wideband or ultra-wideband waveforms are used only for special functions or modes where high resolution is necessary.

Impulse radars are a special class of UWB radars which also operate near base band and therefore often have substantial low frequency content, and typically have very high peak power and short pulse length. These properties, it has been claimed, have some potential for unique performance and these have been the subject of much discussion. Generally, the claims for unique capabilities of impulse radars fall into two categories, as outlined below.

Those which accrue from very high power and/or short pulses. Uniqueness in performance relies on either non-linear effects or on the so-called "precursor" linear effects. For power densities incident on a target which apply for practical radar applications, there is no evidence of non-linear effects at frequencies of interest. The "precursor" effect is discussed in Section V but is commonly understood to be a wideband transient response effect. In these areas, there are no data or theories which support unique benefits from the use of impulse radars.

There do exist situations where it is advantageous to have "short pulse" transmissions. For example, it is conceivable that, for certain short-range applications, transmit-receive isolation could require a "short pulse."

Those dealing with the implementation advantages in simultaneous low frequency and high resolution. There are a number of applications where the combination of high resolution and low frequency is desirable. The most demonstrated is earth penetration but others such as foliage penetration or, possibly, simultaneous low-frequency surveillance and high-resolution target identification, should be considered. UWB radars using either conventional or impulse techniques could accomplish these functions but **impulse radars might have an advantage in implementation** as measured by cost, size, or weight, and deserve detailed examination. Shorter-range applications are most likely to yield this advantage. Very short-range applications gain the additional advantage of not being bound to transmit and receive simultaneously. As a last example, impulse radars might possess some implementation advantage if the target is time-varying (e.g., blade flash from a helicopter).

IV. STATUS

The full Panei was formally addressed by 33 speakers in its attempt to acquire the most recent technical, tactical, and industrial information about UWB technology. (See Appendix A for agendas.) The Panel also sent representatives to the "First Los Alamos Symposium on Ultra-Wideband Radar" and to the Center for Beam Studies at the University of Rochester's Laboratory for Laser Energetics (see Appendix A for agenda and attendees). Altogether, the full Panel convened nine times, sub-panels convened twice, and Panel representatives spent 4 days at the Los Alamos UWB symposium.

A summary of the UWB technologies that the Panel was exposed to, and is aware of, is given in Table 1. The list is by no means complete. It is basea on the Panel's experi‹.ıce and it includes those organizations that are active enough in the UWB area to have participated in "The First Los Alamos Symposium on UWB Radar." The summary identifies organizations and equipment, measurement facilities, and research programs.

A number of the organizations encountered in the course of the Panel's study have had an involvement in UWB technology extending over a decade or more (e.g., NRL, RADC, SRI), and have produced bandwidths ıd/or test facilities which are noteworthy. Among these are

(1) GSSI, which has produced a large number of impulse ground-penetrating radar systems for both military and civilian applications

(2) The Ohio State University/Electrosciences Laboratory, which has employed UWB systems in the measurement of RCS characteristics and radar imaging

(3) Naval Postgraduate School, which has developed a unique UWB indoor range capability.

Finally, the Soviet literature supplied by the Defense Intelligence Agency (machine translations of several books and articles) was concerned with sources, radar target identification, and impulse time-domain diagnostic techniques. These were considered by the Panel to be obvious applications of high-resolution time-domain techniques (see Section VE).

TABLE 1. STATUS OF UWB RESOURCES

PERFORMERS \ TECHNOLOGY AREAS	Switches	Sources	Receivers	Antennas	Ranges	Target I.D.	Spark Gap Tech.	RAM Measurement	Theoretical Studies	Literature Reviews	Foreign Tech. Asses.	EW	Foliage Penetration	HPM	Pulse Power	Diagnostics	Systems	T.D. E.M.	REB
AFWL				o					o					o	o			o	o
ANRO		x		x				x	x								x		
Auburn U.									o									o	
Battelle		o	o	o			o		o	o	o	o		o	o	o			o
BDM						x			x					x	x				
Boeing	x	x							x				x	o					o
Clemson U.										o									
DIA										x	x								
ERIM									o	o									
General Atomics	o	o					o							o	o			o	
General Dynamics		x		x		x			x			x	x	x	x	x	x		
General Research Corp.						o			o										
GSSI	x	x	x	x									x			x	x		
GTRI					o				o							o	o		
HDL	c						o		x					o	o				
Iowa State U.									o									o	
JAYCOR									o										
Kaman Sciences			o															o	
LANL	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Lincoln Lab									x										

TABLE 1. STATUS OF UWB RESOURCES (Continued)

PERFORMERS \ TECHNOLOGY AREAS	Switches	Sources	Receivers	Antennas	Ranges	Target I.D.	Spark Gap Tech.	RAM Measurement	Theoretical Studies	Literature Reviews	Foreign Tech. Asses.	EW	Foliage Penetration	HPM	Pulse Power	Diagnostics	Systems	T.D. E.M.	REB
LLNL	o	o		o					o					o	o			o	o
Maxwell Labs															o				
McDonnell/Douglas		x	x	x		o			x			x		x	x				x
Michigan State U.						o			o										
MICOM												o		o					
MITRE									x										
MRC	x	x	x	x	o	o	o	o	x	o	o	x		x	x	o		o	x
Naval P.G. School	o	o	o	o	o	o			o									o	
New Mexico IM&T						o			o										
NIST							o												
Northwestern U.									o									o	
NOSC	x	x		x	x														
NRL	o	o	o	x	x			x	x	x	o			o			o		
NSWC	o	o					o		o			o		o	o				o
Oak Ridge N.L.									o										
Old Dominion U.	o	o																	
Physics International	o	o		o	o		o	o	o					o	o	o	o		o
Pico Second Pulse Labs		o																	
Power Spectra	x	x																	
RADC	x	x		x	x														

TABLE 1. STATUS OF UWB RESOURCES (Continued)

PERFORMERS	TECHNOLOGY AREAS	Switches	Sources	Receivers	Antennas	Ranges	Target I.D.	Spark Gap Tech.	RAM Measurement	Theoretical Studies	Literature Reviews	Foreign Tech. Asses.	EW	Foliage Penetration	HPM	Pulse Power	Diagnostics	Systems	T.D. E.M.	REB
RADC Hanscom										x										
SELINA										o										
SRI		x	x	x	x	x	x			x		x								
Syracuse U.		x	x				x			x									x	
Tele-Link										o										
The Ohio State U.		x	x	x	x	x	x			x							x			
Thermo-Electron		x	x	x						x					x	x				
Time Domain Systems		x	x	x	x	x														
TOYON							x			x									x	
U. of IL at Chicago										o										
U. of Nebraska										o								o		
U. of Pennsylvania							o			o							o	o		
U. of Rochester		x	x							x						x				x
U. of TX at Austin		o	o		o					o										
Washington U.							o			o										

LEGEND

x Presentation to UWB Panel

o Known to UWB Panel

V. UWB ISSUES

As the Panel deliberations progressed, technical issues began to emerge and the Panel placed the various claims, theories, and measurements into an engineering and scientific perspective.

Claims have been advanced that impulse radars are LPI, that they defeat RAM (radar absorbing materials), that they can thwart radiation-seeking missiles, that they cannot be treated by conventional spectral analysis, and that Maxwell's Equations do not work for impulse radars without a profound reformulation. The Panel was told that specially crafted UWB pulses suffered far less attenuation than classical steady state wave propagation phenomena encountered.

While some of the assertions were transparently unsound, others caused the Panel serious concern. Materials issues that were raised during the course of the Panel's study resulted in a special sub-panel visiting the Laboratory for Laser Energetics at the University of Rochester.

Drawing on the Panel's broad range of constituents from national laboratories, industry, and academia, the Chairman assigned to groups of Panel members (experienced specialists in each appropriate discipline) the task of examining the specific issues for substance. They were asked to organize their professional conclusions and report back to the full Panel. The following sections report their assessments.

VA. Uniqueness

VA.1 Radar Absorbing Materials (RAM)

Some proponents have made claims that impulse radars have a unique ability to "defeat" radar absorbing materials. Even if impulse radars had this capability, this would not mean they had usable counter-stealth potential. It is believed that, for most low-observable targets, target shaping is the primary means of obtaining stealth.

Impulse radar uniqueness claims generally fall into three classes: out-of-band energy related claims (see Appendices C and D), non-linear effects claims, and high electric field strength claims.

Out-of-Band Energy. Most impulse radar counter-stealth claims are based on properties which directly relate to out-of-band energy. Many radar absorbing materials (RAM) are effective over limited frequency bands and are obviously useful only over those bands. Any radar, impulse or conventional (non-impulse) UWB, that utilizes energy which is outside that band will defeat the RAM for that portion of its energy.

These out-of-band properties are linear and conveniently treated using standard Fourier analysis techniques. There is nothing unique about impulse radar's ability to "defeat" this type of RAM in this manner. Any radar that operates outside the frequency band at which a RAM is effective would also "defeat" it. In fact, a radar that operated totally outside the band would be more efficient since less of its energy would be in the band at which the RAM works and therefore more energy would be returned to the radar.

Non-linear Effects. For UWB to exhibit true uniqueness, some non-linear effects would be required. Non-linear effects might be related to extremely strong electric field strengths or possible molecular or atomic relaxation. Although neither of these effects appears to be applicable to real-world radar absorbing materials or useful radar geometries, they are discussed here and in Section IX and Appendix E.

High Field Strength. Calculations have been made that show that the field strength for an extremely high peak power radar (100 GW ERP) located as close as 10 km from a target would produce field strengths five orders of magnitude below the level needed for non-linearities to begin to occur in magnetic materials[1].

Consequently, some high field strength non-linearities could conceivably be excited by placing a sample directly in front of an impulse radar antenna, but they would not be exploitable in the most optimistic real-world impulse radar scenario. The Panel saw no credible evidence, theoretical or experimental, that useful non-linear effects exist.

[1] Muehe, C. E., "Impulse Radar," Lincoln Laboratory Internal Report, 13 February 1989.

VA.2 Exotic Pulse Propagation Effects

Molecular Relaxation and Signal Precursor Effects. These two phenomena have been discussed in relation to the propagation of signals through attenuating media (such as microwave absorbers). The signal precursor phenomenon involves the transient response components of a pulsed signal that propagate through a dispersive attenuating medium faster than the main body of the pulse (hence they are precursors to the steady state signal).

The precursor effect can be thought of as a subset of relaxation phenomena, occurring when the attenuating medium material has a molecular resonance that creates an absorption frequency band, and results in dispersion. Both the relaxation and precursor phenomena are linear effects, and therefore readily treated with existing analysis techniques.

Though the precursor effect is an interesting phenomenon, in the Panel's view it is difficult to imagine a practical radar application for it. The energy that "penetrates" the absorbing medium in the precursor signal is due to spectral components outside of the absorption bandwidth. The energy in the band is heavily absorbed. It would be more efficient to just move the signal carrier frequency out of the material's absorption band. (A narrowband signal positioned above or below the absorptive resonance would achieve more penetration and less distortion.)

The same conclusion is reached for the more general relaxation effects. If there is a portion of a signal's spectrum which avoids absorption, it is most prudent to design a waveform to concentrate its energy in that spectral region. Several UWB proponents had claimed that due to special properties of short pulses, they could penetrate material media with less than exponential attenuation. The basis for this claim was the so-called "Crisp pulse". For an explanation of Crisp pulse, sub-exponential attenuation, and the "Zero Area Theorem," see Appendix D, where these three are explained and it is shown that short pulses do not, in fact, escape the natural laws of propagation.

Self Induced Transparency (SIT). Self induced transparency is a quantum effect phenomenon in which a properly constructed pulse can penetrate an absorbing medium with very little attenuation. Distinct from the relaxation and precursor effects discussed above, the SIT signals are not out-of-band of the absorption. Practical demonstrations of SIT are made at optical frequencies in supercooled materials or rarefied gases. High temperatures and dense media overwhelm the quantum effect exploited by SIT. It is not expected that SIT will be identified with common materials at radio frequencies. See Appendix E for further discussion of SIT.

Low-level Non-linearities. Low-level non-linearities in man-made materials could be used to discriminate targets from (natural) clutter through the detection of frequency harmonics created by the non-linearity. No such effect has yet been identified for materials of military interest. Previous investigations seeking other non-linear phenomena (such as metal-to-metal rectification effects) suggest that it is likely that the level of the harmonic signals will be many orders of magnitude lower than the linear return, making them difficult to detect.

Further discussion of the above effects is contained in Appendices C, D, and E.

V.3 Natural Resonances

It has been argued by UWB radar proponents that such systems are uniquely capable of exploiting the natural (or body) resonances of a target to enhance the target's return and hence improve detection and/or classification.

Natural resonance refers to the fact that targets have natural resonances whose frequencies (but not amplitudes) are independent of aspect angle and polarization. The phenomenon has been measured experimentally and has been described mathematically by the singularity expansion method (SEM). Resonances observed have been from targets with various body sizes and structures, antennas, and from the coupling into and out of cavities (like cockpits). A brief review of the theory of natural resonance can be found in Appendix F.

Natural resonances manifest themselves in the "late-time" or natural response, which is that portion of the radar return that persists after the incident waveform has passed over the target (during which time the "early-time", or forced, response is excited).

Traditionally, all radar applications use only the forced response, typically because the choice of bandwidth and center frequency of the transmitted signal results in a dominance of this term over the natural response. The conventional radar community argues that several factors dictate continued operation in these frequency regimes. These include improved directivity and radiation efficiency for a given antenna size, and a reduced EMI environment, particularly compared to operation in the 1 to 100 MHz range required to excite whole body resonances on bomber- and fighter-sized targets. Furthermore, they point out that exploitation of natural resonances does not uniquely require ultra-wideband waveforms; the use of one or more narrowband signals "tuned" to the discrete natural resonances could exploit the increased target radar cross section (RCS) at these frequencies without the need for UWB (or impulse) operation. Even with such waveforms, little enhancement is seen for low-observable (LO) target detection since RCS reduction is achieved primarily through shaping, which inherently results in weak (low-Q) body resonances. Similarly, target classification using resonances is hindered by the fact that many Soviet and US targets have comparable dimensions, and hence resonance frequencies. As a result, resonance ID schemes are less robust than high-frequency one- or two-dimensional (ISAR) methods, for example. Finally, the conventional radar community accurately notes that the coefficients of the singularity expansion <u>are</u> dependent on the aspect and polarization of the incident wave. Since the coefficients determine the extent to which each resonance is excited (and hence its detectability above clutter and/or noise), the design of a radar exploiting natural resonances must still account for the aspect and polarization dependence of the target in assessing its performance in detection and classification applications.

The proponents of UWB/natural resonance concepts counter these arguments as follows. The need for robust operation against a variety of targets, each having different sets of natural resonances, dictates the need for moderate- to large-bandwidth signals, which, when combined with low-frequency occurrence of the resonances mentioned above, inherently results in the use of ultra-wideband (rather than discrete, narrowband) signals. The bandwidth requirement is further supported by the need for sufficient resolution to isolate the target from clutter, and to ensure excitation of enough resonances on any given target so as to allow for drop outs due to the aspect or polarization sensitivity of the coefficients (particularly in identification applications). Proponents also claim that these ultra-wideband waveforms can be efficiently radiated using impulse implementation and unique antenna designs. Directivity is achieved using time-domain beamforming methods which are purported to be unique to ultra-wideband signals. This last claim has led the UWB Panel to recommend a study specifically devoted to time-domain beamforming techniques and their impact on radar system performance (see Section IXC). Finally, UWB proponents argue that target identification is more robust using resonance (rather than imaging) methods because of aspect-independence of the SEM poles and the smaller database (poles versus multiple images) required for each target. Similarly, target detection is claimed to be enhanced, despite the use of shaping, because of the extremely low frequency content of the waveform.

It is important to note that there is no debate over whether or not a particular UWB radar implementation affects the occurrence of natural resonances. For example, measurements presented by Mr. McCorkle (HDL) and Mr. Hansen (NRL) to the UWB Panel, and by Dr. Van Blaricum (Toyon), and Dr. Young (The Ohio State University) at the "First Los Alamos Symposium on Ultra-Wideband Radar" all demonstrated impulse and swept frequency techniques to be equivalent. Impulse advocates correctly point to natural resonance as an application for impulse, and swept frequency advocates also correctly point to the same application.

In order to resolve these issues, the Panel recommends that an end-to-end system analysis comparing conventional (chirp or phase-coded) and impulse designs for a medium-range non-cooperative target recognition (NCTR) radar based on natural resonance research results be performed (see Section IX). Since the highest-amplitude natural resonances tend to be at relatively low frequencies (below 2 GHz) and since the impulse transmitter promises "wall-plug to air" efficiencies in the 50 percent range at such frequencies, it appears that this application is a likely candidate for the impulse implementation to have an advantage. The result of the analysis should quantify how trade-offs in each system affect the sensor performance.

Interestingly, it was shown in a previous analysis that, depending on the available energy per pulse, either a narrowband or an ultra-wideband signal was optimum for detecting a target in clutter using natural resonances (I. J. LaHaie, et al., "An Evaluation of Nonsinusoidal Radar Techniques", ERIM TR-171300-10F to DARPA/ONR, Contract No. N00014-83-C-0754, June 1985).

VB. Counterstealth Detection

Recognizing that the counterstealth potential of impulse radars has become highly political, the Panel wishes to clarify what avenues are available for a radar to be "anti-stealth," and to offer comments on the claims that have been made in this area. In general, it is clear that impulse radar is not "inherently anti-stealth."

There are three technical issues which could relate to counterstealth potential.

The first is that of non-linear responses due to very short pulses ("transients") of very high peak power impinging on either the RAM (radar absorbing materials) or composites and in some way "defeating the RAM." In response to this issue, even if the RAM were "defeated," it must be recognized that the primary technique for achieving low radar cross section is shaping, not RAM. Secondly, it is noted that, at ranges of any tactical interest (e.g., 10 km), a practical radar (even a 10-GW impulse radar) will not be able to utilize material non-linearities. Field strengths are too low to excite material non-linearities, and all observed effects, including linear "precursors," are due to "out-of-band" operation. It is worth noting that standard measurement and diagnostic techniques routinely used by the stealth community deal with this issue completely.

The second technical issue is the frequency of operation. Low frequencies (VHF and UHF) can exploit target resonances effects that are independent of shaping and only a function of size. This, however, is true for any radar operating in those bands and the advantages of one form of the radar or another accrue only in the details of implementation.

The third issue is the bandwidth of the stealth techniques, which do, of course, have finite bandwidth. Both high- and low-frequency, wide-bandwidth radars have been examined in some detail. Wide bandwidth does compound the difficulty of some stealth techniques but all demonstrated absorber effects are entirely due to "out-of-band" energy. Consequently, the use of impulse or conventional (non-impulse) approaches to exploitation of frequency/bandwidth is again an implementation issue. Conventional (non-impulse) approaches can provide all that is needed, but impulse techniques may yield lower-cost, lighter-weight implementations for some scenarios. The Panel could find no adequate comparisons that would allow conclusions on implementation questions.

VC. ECM/ECCM

VC.1 Interference Resistance of Wideband Radar Waveforms

An impulse or short-pulse radar waveform has an inherent resistance to interference or barrage jamming which is equivalent to that of a conventional pulse compression waveform with the same energy spectrum. These conditions also assure that these waveforms will perform equally well against a uniform, or white noise, background. Furthermore, the interference resistance of these waveforms is directly proportional to their bandwidth.

To see why this claim is true, consider the following equal-bandwidth waveforms:

WAVEFORM	TIME FUNCTION	FOURIER TRANSFORM
Short Pulse (monocycle)	$s_1(t)$	$S_1(\omega)$
FM Sweep	$s_2(t)$	$S_2(\omega)$
Bi-Phase Coded Pulse	$s_3(t)$	$S_3(\omega)$

Let the common bandwidth of these signals be B and, for convenience, normalize these waveforms to unit energy.

$$\int |s_k(t)|^2 \, dt = \int |S_k(\omega)|^2 \, df = 1 \tag{1}$$

The spectral densities $|S_k(\omega)|^2$ of these waveforms have a similar shape, attaining a maximum near the center of the band, and gradually falling to zero at the band edge, as illustrated in Figure 1. Waveforms 2 and 3 have spectral densities which have a great deal of fine structure, reflecting the large variations in the phase of their spectra. For many purposes, this fine structure may be ignored and the spectral density approximated as

$$|S_k(\omega)|^2 = B^{-1}; \ \omega \text{ in band} \quad . \tag{2}$$

As shown below, the vulnerability of a waveform depends on the ability of a jammer to exploit the fine structure of the waveform spectrum.

The spectral characteristics of the three exemplar waveforms are typical of any radar waveform that has well-controlled range sidelobes, since the matched filter receiver output is determined by the spectral density, Equation (2).

The optimum radar receiver (against white noise) is the matched filter, whose frequency-domain representation is given by the complex conjugate of the Fourier transform of the pertinent waveform. The voltage response of the matched filter may be written as the Fourier transform

$$V_k(t) = \int |S_k(\omega)|^2 \, e^{j\omega(t-T)} \, df \quad . \tag{3}$$

Given that the approximation of Equation (2) is valid, it is seen that the matched filter output is a short pulse of duration B^{-1} and peak value of unity, independent of the waveform. This conclusion may be validated by a detailed calculation of the integral, Equation (3), using the exact expressions for the power density spectra. The fine structure in the spectra shows up as fine grain details in the range sidelobes of the output waveform. This is simply stating in mathematical terms the fact that the output of a pulse compression filter is a short pulse with complex, but generally low range, sidelobes. From the viewpoint of interference resistance, however, the crucial point is that attention can be concentrated on the matched filter interference response, since the signal response, in the normalization, is independent of waveform selection.

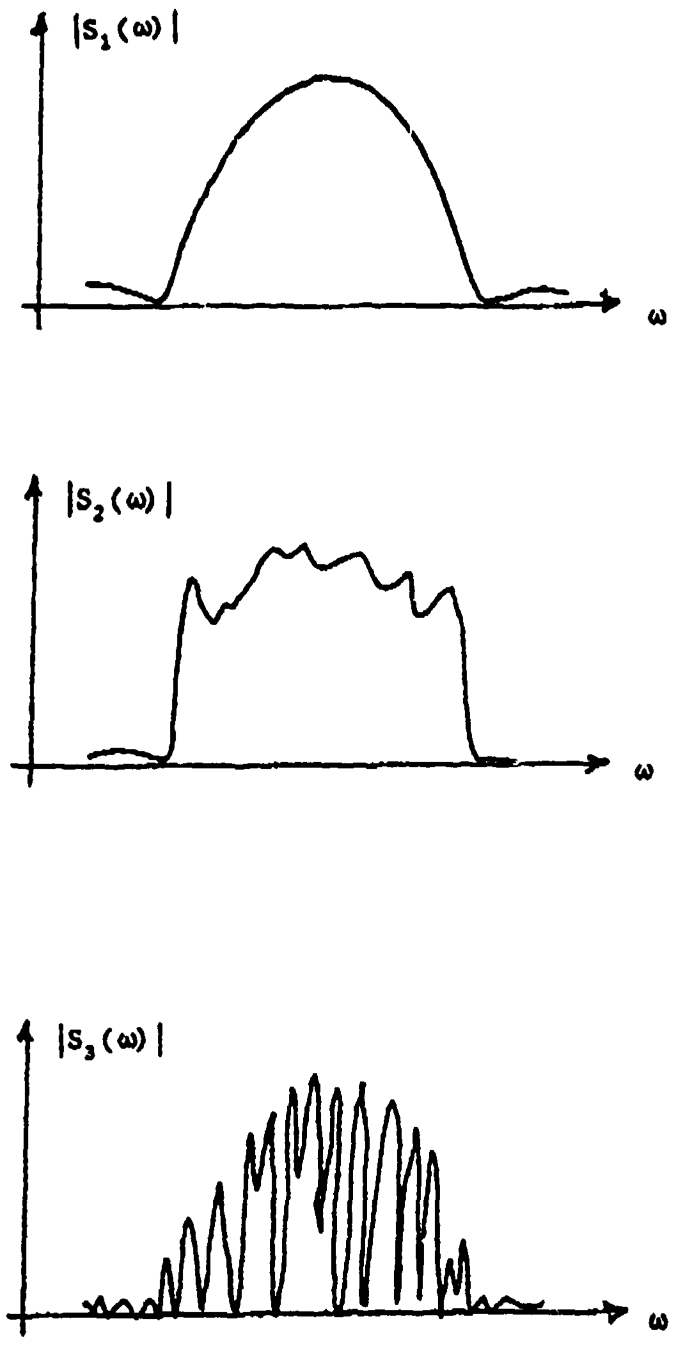


FIGURE 1. POWER SPECTRA OF THREE EQUI-BANDWIDTH RADAR WAVEFORMS

Consider a narrowband interferer or jammer which can be assumed to be the sinusoidal function A sin $\omega_I t$. The matched filter is a sinusoid of magnitude A $|S_k(\omega_I)|$, which in the light of Equation (2) is independent of waveform. The spectral fine structure of the pulse compression waveforms causes the sinusoidal response to fluctuate as a complex function of the interference frequency ω_I, but unless the jammer has a detailed knowledge of the waveform, only the waveform average power is of importance.

A similar conclusion holds when the interference is a random noise or barrage jammer with power spectral density $\Phi_I(\omega)$. In this case, the matched filter output will be a random noise process with power spectral density

$$|S_k(\omega)|^2 \Phi_I (\quad \Phi_I (\omega)/B \tag{4}$$

which is independent of the radar waveform and inversely proportional to the radar bandwidth. Furthermore, if the jammer average power is held fixed, the output power of the matched filter is independent of the jammer bandwidth (as long as the jammer bandwidth is contained within the radar bandwidth).

The above discussion has shown that the vulnerability of a radar to non-specific (or dumb) jamming or unintentional interference depends only on the radar bandwidth, and is independent of the jammer bandwidth (until the jammer bandwidth extends beyond the radar band limits). If the jammer knows the details of the radar waveform, it may use a specific waveform tailored to maximize the response of the matched filter. This is probably easiest to do for the short-pulse waveform, and somewhat more troublesome for the FM sweep waveform. If the phase code of the bi-phase coded pulse is cryptographically secure, a specific jamming waveform tailored for this class of waveform will be impossible to generate.

In the conventional electronic countermeasures (ECM) problem, the broadband noise jammer bandwidth generally exceeds the radar bandwidth. In the UWB radar problem, many existing broadband noise jammers will be completely within the radar bandwidth. Existing non-specific jammers, intended for use against conventional radars, are effective against UWB radars. All jammers on an electronic warfare platform which are in-band will contribute to the overall jamming effectiveness. Their relative effectiveness is related to the radar bandwidth, as was shown in Equation (4).

Systems that would not normally be considered jammers can interfere significantly with the operation of a UWB radar. Individual narrowband interferers (such as radio and television broadcasts) could be notched (nulled) out in the UWB receiver. However, the commercial broadcast bands are probably unusable to the UWB radar because of the density of emitters. Notching becomes less desirable on broadband noise jamming, though the degradation of radar performance could be graceful as the usable bandwidth decreases.

Deceptive Jamming

Another class of countermeasure, deceptive jamming, can be used to foil target identification schemes. A typical deceptive jammer is a coherent repeater that retransmits the incident pulse. Used against a UWB short-pulse radar intended for non-cooperative target recognition, the repeater could send a series of pulse replicas in response to each incident pulse. This would be intended to mask the true target return and could be designed to generate a false identification (making a drone look like a bomber, for example).

When "straight through" repeater jammers are used against high range resolution pulses, delays in the repeater could leave the initial target skin return uncovered. Whether this represents a vulnerability for the target would depend upon the specific track logic in the radar. For example, if the jammer attacked the AGC, then the skin return could be suppressed.

At the present time, the only practical implementations found in radars with greater than 1 GHz bandwidth are linear FM (chirp) with stretch processing, bi-phase coding, or short-pulse (impulse) designs. Because the linear FM waveform is predictable, several issues arise when smart, deceptive jamming is considered.

First, in the case of the chirp system, a simple frequency shift in the jammer can place a false target either ahead of or behind the range of the true target. This possibility exists because of the predictability of the linear FM waveform, and can be countered by a cryptographically secure phase-coded radar that changes code on a pulse-to-pulse basis, or by an impulse radar using a random PRF jitter. Obviously, randomly varying the linear FM sweep rate would have a similar effect, if implementation problems could be solved.

Second, if stretch processing is used in a chirp radar, a smart deceptive jammer signal is not filtered out as noise or barrage jamming signals are. As a result, the radar is much more sensitive to saturation by a smart jammer than by noise.

In conclusion, it is safe to say that whether a system is implemented with impulse techniques or the more conventional chirp and phase coding techniques, performance in the presence of smart jamming requires careful design. One cannot categorically say that either approach is a clear winner.

VD. Interceptability of Impulse Radar Signals

Introduction

The high power required of most radars make them relatively easy to intercept by an Electronic Support Measures (ESM) receiver. It is not unusual for good intercept receivers to detect radar signals radiated by the antenna sidelobes at long ranges, even beyond the normal radar horizon in some cases. (In fact, radar signals are usually so strong that the sensitivity of the intercept receiver is sometimes deliberately reduced so as not to overload the ESM system with more radar signals than can be processed.) Claims have been made that impulse radar cannot be detected by ESM receivers and can be classed as having low probability of intercept (LPI). Unfortunately, none of the claims that impulse radar is LPI have been substantiated by calculations, measurements, or other qualitative or quantitative arguments. The purpose of this discussion is to review the susceptibility of impulse radar signals to intercept by ESM receivers.

LPI Radar Design Principles

The high power required of radar transmitters, as well as the variation of the radar signal as R^{-4} (where R = range) as compared to the R^{-2}

variation experienced by an intercept receiver, gives the advantage to the intercept receiver. In spite of all the efforts to make an LPI radar, it is not practical for a military radar to completely "hide" its transmissions and still perform its mission. The radar designer, however, has some options available for reducing the interceptability of radar signals. Basically, the chief principle of LPI radar design is to use a signal that intercept receivers are not designed to detect. The classical intercept receiver is designed to detect the type of radar signals that now exist. The nominal signal might be a 1-μs pulse with a 1-KHz pulse repetition frequency. Any signal vastly different from this nominal radar waveform will not be as readily detected. The impulse radar waveforms with pulses of a fraction of a nanosecond are quite different from the signals for which most intercept receivers are optimized.

The LPI radar designer will try to spread the radar signal energy over as wide a spectrum as possible, use a high duty cycle (a low peak power), and as low a transmitter power as possible. LPI designers will also try to employ a low antenna scan rate, agile waveforms to negate interceptor processing gain, and power programming. The chief attribute of an impulse radar for LPI is that it spreads its spectrum over a wide band. Even though the bandwidth of an impulse radar is far greater than that of conventional radars, it is not that much greater than the bandwidth of some of the better LPI radars. Furthermore, if the LPI radar used a coded waveform having the same bandwidth as the impulse radar, it would have, as indicated before, the advantage in covertness of the pulse compression ratio. The best of the so-called LPI radars are not undetectable, they are only less detectable than other radars.

Table 2 gives the impulse radar intercept range for various assumptions. The table indicates that the intercept range is large even when detecting sidelobe radiated energy; it being 506 nmi for $I = 10^4$, a properly matched intercept received, and a sidelobe level of 40 dB down. There is actually a question of whether such a good sidelobe level can be achieved for an impulse radar. To achieve it requires either a large number of antenna elements (like 10,000) or a dense packing of the radiating elements (a spacing much less than $\lambda/2$).

Table 2. Impulse Radar Target Detection, Intercept and Cross-Over Range Comparison (Pulse Width = .1 ns, P_{av} = 1 kW, Radar Antenna Gain = 30 dB, Radar Receiving Aperture = 20 ft^2, Intercept Receiving Aperture = 1 ft^2, Intercept Receiver RF Bandwidth = 10 GHz)

P_T	Radar Prf (pps)	Number of Pulses Coherently Integrated I	ESM Video Time Const. (ns)	0.1 m^2 Tgt. Det. Range (nmi)	Mainlobe Intercept Range (nmi)*	Cross-Over Range (nmi)
10 GW	10^3	10	0.1	47	1,600,000	0.0014
10 MW	10^6	10^4	0.1	47	50,600	0.043
10 GW	10^3	10	100	47	50,600	0.043
10 MW	10^6	10^4	100	47	1,600	0.72

$\left(\frac{S}{N}\right)_{RADAR} = 5$ $P_D = .9$, $P_{fa} = 10^{-6}$ $F_R = 10$ = Radar Receiver NF

$\left(\frac{S}{N}\right)_{INTERCEPT} = 20$ $P_D = .5$, $P_{fa} = 10^{-6}$ $F_I = 10$ = Intercept Receiver NF

*The sidelobe intercept range is one hundredth the values given if the sidelobe level is 40 dB down.

The range at which the interceptor detects the radar can be reduced by having the radar transmitter peak (or average) power decreased. This will, however, in turn decrease the radar detection range for the target of design cross section σ. As the transmitter power is decreased, there is a range reached at which the interceptor detects the radar at the same time the radar detects the target of cross section σ, the interceptor being assumed to be on the target. This is called the cross-over range. Values are given in Table 2 for the cross-over range for the cases considered. If the transmitter power is decreased to some value below the value needed to achieve range cross-over, then the radar will detect the target before the interceptor, that being assumed to be on the target.

Appendix G gives an analysis of the intercept range. It also gives some measured results. It can be concluded that if the intercept receiver is properly designed, there will be little problem in detecting the signal even when it is radiated from the radar antenna sidelobes.

The major conclusion by the Panel is that even though current intercept receivers are not specifically designed for impulse radar or ultra-wideband (UWB) signals, these signals can be detected at long ranges and cannot be considered to be LPI. They might have a lesser probability of intercept than conventional radar signals, but they are not undetectable. In fact, a pulse compression radar using a random or pseudo-random waveform having the same bandwidth and energy per pulse as the impulse radar would be more difficult to detect. It would have an advantage in covertness of the pulse compression ratio. Current intercept receivers fail to provide information about the impulse radar signal (such as frequency, pulse duration, pulse repetition rate, etc.) since they were not designed for such signals. There is no reason to believe that this would occur with intercept receivers designed specifically for detection and recognition of the impulse radar signal. Therefore, the claim that impulse radars are LPI cannot be substantiated.

VE. Foreign Interests

There appears to be little effort in impulse radar in foreign nations other than the USSR, except in the very short-range application of underground exploration. There is virtually nothing in the open literature on applications to conventional radar. A little effort has been made in Italy on detection methods where the target echo has been resolved into many scatterers, but apparently no efforts have been undertaken on radar systems. While there may be classified efforts, none of the current Panel's contacts seemed to be aware of their existence.

The Panel did not find evidence of any USSR air surveillance or tracking radars that use impulse techniques.

VI. POTENTIAL RADAR APPLICATIONS

The decision process which would determine the approach that should be used for any particular radar application of UWB technology is illustrated in Figure 2. Generally, as discussed in Section V, there are no non-linear effects that could be exploited, at least in systems of interest in this study.

Phenomenology such as clutter and multipath will be important in determining whether UWB techniques are applied to radar. There are, of course, other factors, such as target size and vulnerability, but these are generally understood.

If UWB techniques are applied to radar, the issue between "conventional" (non-impulse) approaches (e.g., coded waveforms) and impulse techniques is one of implementation cost, weight, or complexity. This is the greatest outstanding uncertainty in determining the value of impulse techniques.

There are a number of applications in which some have suggested there may be an advantage over conventional radar in using impulse radar techniques. Generally, these are cases which exploit simultaneous operation at low frequencies and fine range resolution. From the limited work done to date in examining comparisons, it appears that the shorter-range applications are likely to offer the most potential for impulse radar advantage.

However, there have been inadequate quantitative comparisons between impulse and conventional implementations of the same bandwidth to understand the trade-offs and derive conclusions. The comparisons that have been done have dealt with longer-range systems where impulse systems appear to be unattractive.

During the course of the Panel's briefings, it was unable to identify a meaningful carefully thought out engineering study of an impulse radar design with credible performance calculations (even at the block diagram level). Those presentations that made attempts at this had severe short comings. The following are typical inconsistencies in models presented to the UWB Panel.

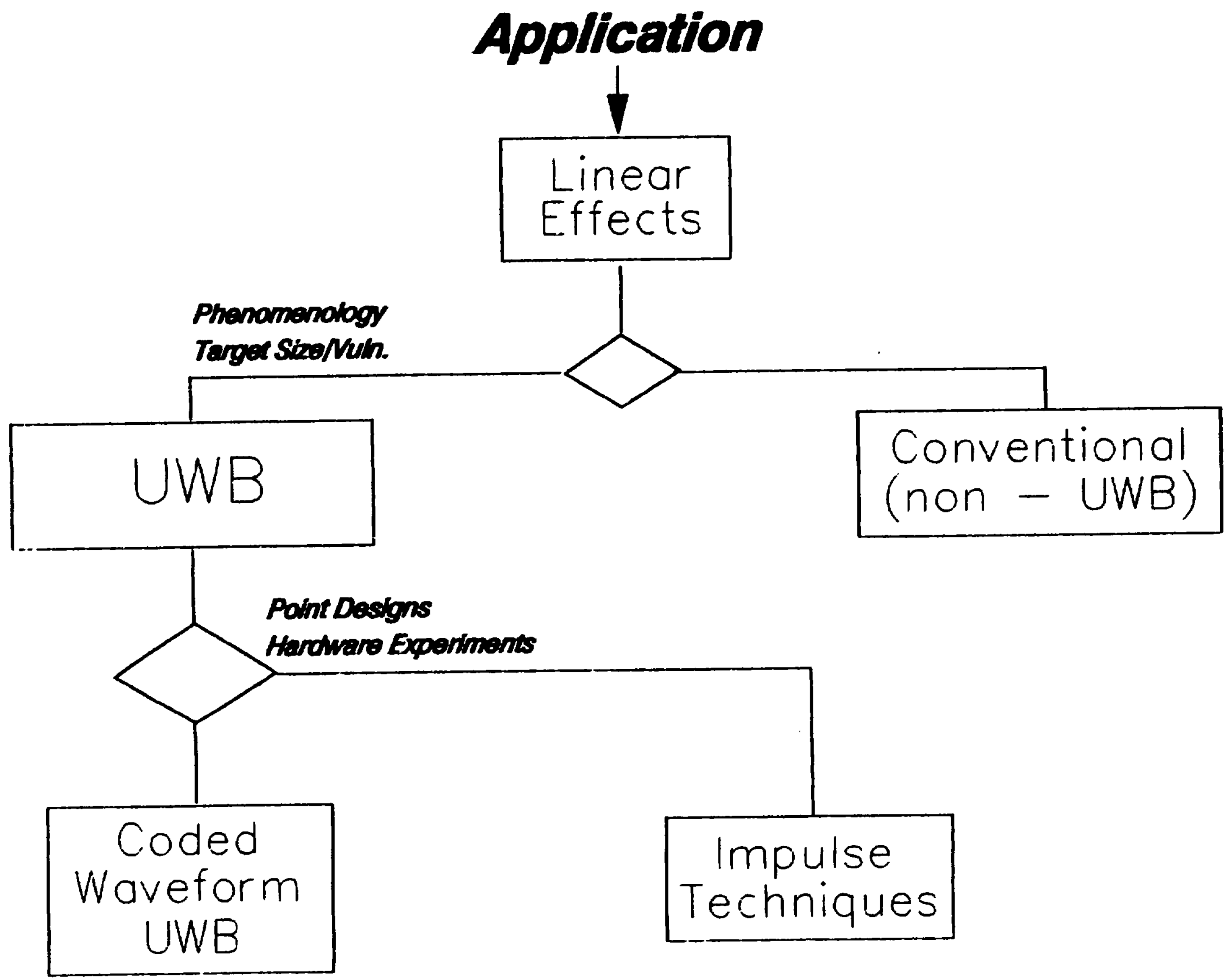


FIGURE 2. DECISION TREE FOR RADAR APPLICATIONS

- Flaws were evident, such as employing the low-frequency propagation attenuation in range while still assuming the high-frequency performance associated with short-pulse spectra.

- Short-pulse discrimination against multipath was often assumed at low frequencies for low-flying targets over smooth water, when in reality the LF components will cancel out (null on the horizon effect).

- It was usually assumed that the antenna had no variation in gain over the bandwidth of the transmitted impulse, and that the RCS was also frequency-independent.

- Questionable assumptions were often asserted with respect to clutter characterization.

These factors are examples of the items that need to be addressed in any broadband performance characterization, as with the impulse radar system.

At the assertion level, the Panel was shown superficial comparisons which do not address all, or even the most important, issues of the system design, and most of these did not reach credible conclusions. In order for an objective comparison to be fairly accomplished, a set of performance specifications have to be determined and the detailed design of each type of approach to meet those specifications must be undertaken. This must include all issues of clutter rejection, search rates and volume, signal and data processing, and the like. As a minimum, each of the comparative designs should provide the following:

- Complete block diagram; including transmitter, antenna, power supplies, receiver, signal and data processing elements, and all the ancillary equipment necessary for stand-alone operation.

- Aperture (antenna) designs and sizes.

- "Sizing" of each block with all the relevant parameters, such as some detail of the receiver, its noise figure, signal processing, data processing, data rates, bandwidths, etc.

- Estimates of size, weight, prime power, and cost with corresponding rationales of the values chosen.

- Exposure of all assumptions, techniques, etc.

- Complete discussion of all issues and how they were treated in the hardware design.

Initially, the Panel intended to undertake these point designs and analyses with the resources of the Panel, but it quickly became apparent that the complexity of the trade-offs and the number of issues that needed to be addressed to make reasonable comparisons for each application were more than could be properly done in the time available. The Panel therefore recommends that the Government arrange for such designs and analyses by independent contractors. For guidance, the Panel sees the level of effort to be on the order of 1 to 2 person-years per application. It is important that each cover all the relevant issues and do so in enough detail that the comparison is complete.

The comparative design study described should be viewed only as a first, but important, step in reaching a conclusion. Based on the results, it may be essential to construct one or more prototypes to explore issues which relate to hardware details. However, no consideration should be given to this step until the design-level comparisons are complete.

The applications chosen for analysis should be carefully selected to suggest real benefits from the impulse approach. The selection is properly biased in this direction since conventional approaches are already generally understood but not fully exploited. With this in mind, the Panel identified four typical applications of varying character, each with potential benefits from simultaneous low frequency and imaging quality range resolution:

- Short-range, ground-based, moving target detection radar, penetrating foliage, walls.[1]

- Short-range, airborne imaging radar for foliage penetration.

- Ground-based, air defense radar with capabilities for non-cooperative target identification.

---

[1]Mine detection is also a short-range, ground-based application in which impulse radar performs well. However, the main issue for mine detection is *discrimination*, not detection.

- Radar for point defense against low-observable sea skimmers.

The first two applications are excellent candidates for impulse implementation. A study of the other two is needed to understand the contribution that such techniques can make to special air-defense needs. Applications to any longer-range systems should await the results of these studies before further resources are expended.

Ultimately, the criteria for comparison should be weight, power, and cost. However, the two designs must meet all the performance goals and address all technical issues for these comparisons to be valid.

Appendix I provides some detail on each of these four applications selected by the Panel as candidates for comparison, and outlines at least the principal issues involved in each.

VII. ECM AND WEAPONS APPLICATIONS

Several potential ECM and weapons applications of UWB techniques were presented to the Panel early on. The Panel was concerned that it would be difficult to do a thorough assessment in this area because of security and company proprietary restrictions. The Panel then learned that the DoD had established an in-house committee (which would not be limited by these restrictions) that would review ECM and weapons issues as part of a broader assignment. Therefore, the Panel, with the agreement of the Sponsor, dropped this effort. A Classified summary of the sub-committee's initial efforts in this area has been separately forwarded to the Sponsor.

VIII. CONCLUSIONS

After extensive and detailed consideration of the issues, status, and applications of UWB technology, the Panel reached the following specific conclusions on impulse technology and its associated applications.

(1) THERE IS NO CREDIBLE EVIDENCE OF UNIQUE PHENOMENOLOGICAL CAPABILITIES

Although several proponents of novel descriptions of field-matter interaction phenomena presented their thoughts on precursors, Crisp pulses and (so-called) sub-exponential pulses, the Panel was presented no credible evidence that these phenomena can be uniquely exploited by impulse radars. If anything, it appears that conventional radars may actually possess an advantage with these phenomena. It was found that (excluding intensity-driven propagation non-linearities) there exists no "short-pulse" or pulse-unique phenomena and no way to avert the attenuation encountered in lossy media. The Panel believes that the chance of finding such a phenomenon is extremely remote. [Panel concern was raised about serious physical and analytical misconceptions that had been advanced.]

(2) IMPULSE RADARS ARE NOT INHERENTLY ANTI-STEALTH

The Panel concluded that impulse radar is not "inherently anti-stealth." The primary technique used for achieving low radar cross section is shaping. Low frequencies (HF and VHF) can exploit target resonance effects which are independent of shaping and only a function of size. This phenomenon, however, holds for any radar operating in those bands and impulse radars have no unique advantages against shaping.

There are no effects in radar absorbing material (RAM) that are unique to impulse radar. Field strengths in practical applications are too low to excite material non-linearities. All observed effects are due to "out-of-band" operation (with respect to the RAM) and predictions to the contrary are due to a misunderstanding of electromagnetics. Standard measurement and diagnostic techniques routinely used by the stealth community deal with these issues completely.

(3) **IMPULSE RADARS POSSESS NO SPECIAL LPI CHARACTERISTICS**

To make a radar's signal more difficult to intercept, radar designers resort to the use of complex waveforms and large processing gains. Even so, it is difficult to make a radar hard to detect even in the sidelobe region. The Panel concluded that the impulse radar, which typically has less processing gain, has no special LPI characteristics and is readily detectable by an appropriately designed intercept receiver.

(4) **ALL RADAR APPLICATIONS PRESENTED COULD BE PERFORMED BY CONVENTIONAL (NON-IMPULSE) TECHNIQUES**

For every application presented, a counter example using a conventional radar was found. (Usually the conventional radar possessed superior advantages.) The Panel saw no applications for which only an impulse radar could work.

(5) **IMPULSE RADARS ARE USEFUL FOR TERRAIN PROFILING, GROUND PROBING, AND DIAGNOSTICS--ALL SHORT-RANGE APPLICATIONS**

Impulse radars are quite practical for certain diagnostic and media-probing applications. They have much in common with traditional TDR (Time-Domain Reflectometry) techniques. The useful demonstrated results in this area were fairly impressive. The utility of impulse radars for detecting buried and obscured objects is primarily due to the relatively small attenuation suffered by the low-frequency components which are launched and the narrow pulse width which permits short-range clutter rejection. The range for impulse radars, however, is relatively short.

Terrain profiling can be done at higher frequencies, but terrain profiling through foliage requires low frequency and high resolution.

The Panel suggests that impulse radar probably represents the most cost-effective solution for the terrain profiling and ground probing applications.

(6) **APPLICATIONS EXIST WHERE IMPULSE RADARS MIGHT BE MORE EFFECTIVE THAN CONVENTIONAL APPROACHES DUE TO POTENTIAL OF LOWER COST AND LIGHTER WEIGHT**

Impulse radars do have specific advantages for certain applications with regard to size, cost, weight, and ruggedness. As such, it is quite possible that they will proliferate as economical devices for short-range surveillance and buried-object detection.

(7) **THE AVAILABLE ANALYSIS TOOLS ARE ADEQUATE AND APPROPRIATE FOR DEALING WITH IMPULSE RADAR PERFORMANCE**

Impulse radar involves no new or unknown principles. Excluding intensity-driven non-linearities and quantum phenomena, which will not occur at practical field levels, the Panel concluded that classical linear, time-invariant systems theory, conventional statistical estimation and detection theory, and Maxwell's Equations fully describe all the phenomena presented that relate to impulse and non-sinusoidal radars. (It was observed that analytical tools had, on occasion, been seriously abused by some proponents--leading to erroneous physical and analytical assertions.)

(8) **ADVANCES IN SOURCES FOR GENERATING WAVEFORMS AT HIGH POWER ARE IMPRESSIVE AND MAY BE PROMISING FOR CONVENTIONAL AS WELL AS IMPULSE TRANSMITTERS**

The Panel concluded that significant advances are being made in various high-power switch and source technologies. Power levels and claimed efficiencies are impressive. It is possible that conventional RF generators may benefit from these results. Applications of this technology may go well beyond radar applications.

(9) **IMPLEMENTATION IS A CRITICAL ISSUE--FEW VALID COMPARISONS OF IMPULSE WITH CONVENTIONAL RADAR TECHNOLOGY HAVE BEEN DONE**

Lastly, the Panel concluded that there is a scarcity of valid comparative systems analyses. Implementation of an impulse radar system is a critical issue and would involve major expense. For this reason, valid engineering comparisons must be conducted to confirm the validity of the promising practical aspects of this technology before any commitment is made to systems developments.

IX. RECOMMENDATIONS

The assignment of the Ultra-Wideband (UWB) Radar Review Panel was to identify and prioritize UWB research to be pursued and to designate intriguing new areas to be exploited. Throughout the study, the Panel heard presentations on the most recent work in a number of areas relevant to UWB technology. The Panel was also exposed to a number of faulty concepts, erroneous applications of electromagnetic theory, and obscurely-presented ideas which, to a nonspecialist, might seem plausible. In this regard, the Panel has gone beyond its original assignment and has examined the underlying issues and identified (and, to the extent possible, corrected) fallacious assertions. The Panel's recommendations are intended to identify both research to be pursued and errors to be avoided in future investigations.

A summary of the Panel's recommendations is presented first, with the detailed rationale following.

(1) IMPULSE AND CONVENTIONAL RADAR POINT DESIGNS	The Government should fund the analyses of point designs in four critical radar-application areas (as outlined in Section VI). The four analyses will each directly examine and compare implementation trade-offs for impulse and non-impulse radar point designs for a specific set of performance specifications.
(2) CLUTTER MEASUREMENTS AND ANALYSES	A study of the fundamental behavior of clutter statistics under the conditions of widespread frequency components and reduced mainbeam resolution cell size should be performed. The clutter study should be very closely coordinated with the point design studies, especially in terms of the size and shape of the resolution cell dictated by each of the point designs.

(2) CLUTTER MEASUREMENTS AND ANALYSES, cont'd

The study should include the development of an appropriate dependence on center frequency and a formalism for computing the total clutter power contributions from mainbeam and sidelobes of the antenna system.

The panel recommends that no system development be undertaken until the results of recommendations (1) and (2) are assessed and demonstrate the military values of such system(s). NOTE: This is not meant to exclude the technology-oriented investigations in progress at several Government laboratories which are aimed at understanding the technology and implementation implications of such systems.

(3) UWB ANTENNA PATTERN CHARACTERIZATION

A proper mathematical space/time formalism and subsequent engineering analyses to characterize the range and angle patterns of ultra-wideband linear and planar antenna arrays should be accomplished.

(4) TRANSMITTER/SOURCE DESIGN

Although the continued development of potential impulse radar source technologies can be expected, it is recommended that these technologies be critically and thoroughly evaluated. Given the present capabilities of time-domain electromagnetic modeling, it is also recommended that a careful analysis and evaluation of antenna structures appropriate for impulse radar be carried out.

(5) MATERIALS INTERACTIONS

The Panel recommends against the funding of any system studies based upon unsubstantiated materials phenomena.

(a) Linear Phenomena. The Panel is convinced that conventional electromagnetic theory yields a correct description of the linear phenomena presented and recommends against funding studies of these effects for radar applications.

(5) **MATERIALS INTERACTIONS, cont'd**

(b) Non-linear Phenomena.

(i) Self Induced Transparency. The Panel recommends that DoD sponsor a modest effort to document the characteristics of self induced transparency relevant to possible contributions to military systems. This work could be accomplished as part of the JASONS' 1990 Summer Study, a National Science Foundation effort, or funded University research.

(ii) Harmonic Effects. The Panel recommends against the funding of investigations of harmonic generation as an impulse radar signature.

(iii) The Panel recommends that no measurement programs of any kind for the investigation of non-linear effects in stealth materials or vehicles be funded.

IXA. Impulse and Conventional Designs

It is recommended that the Government undertake point designs and analyses of each of the four applications described in Section VI and Appendix I, to get comparisons of the implementations using impulse and conventional approaches.

These analyses, each looking at both approaches to a specific set of performance specifications, should be undertaken by competent and independent investigators at modest levels of effort (e.g., 1 to 2 person-years each). These analyses should be subjected to critical review both during the course of the effort and at the conclusion.

These design study analyses should not be viewed as either an endorsement of impulse radars nor an end unto themselves. They are the first step in determining the relative merits of conventional, non-impulse UWB, and impulse radar approaches. Figure 3 illustrates the overall framework into which these studies fit.

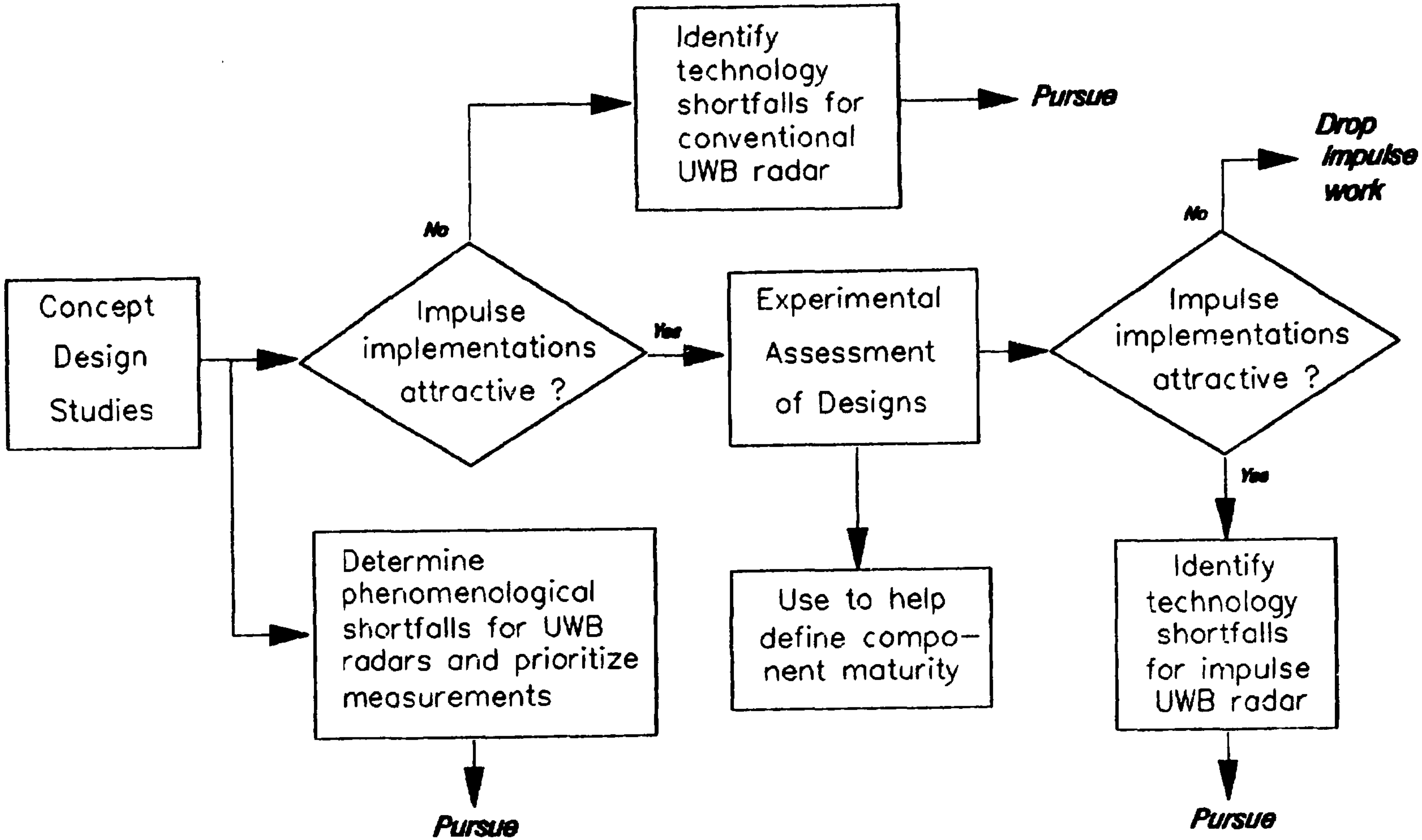


FIGURE 3. FRAMEWORK FOR COMPARATIVE DESIGN STUDY ANALYSES

IXB. Clutter

The proposed advantages of UWB radar systems in mitigating clutter for detection focus on the reduction in clutter cell size that occurs in such systems. This small clutter cell is multiplied by the narrowband average clutter cross section to arrive at the smaller clutter effect. This simplistic approach considers neither the effect of the cell size on the nature of the clutter statistics nor that of the wide frequency band on the value of the mean clutter reflectivity. Numerous programs using high-resolution systems have shown that reduced cell size leads to non-Rayleigh scattering statistics for land and sea clutter. Some aspects of terrain scattering for UWB signals have to be resolved before the actual level of clutter effects on such systems can be established.

The two major questions which impact the characterization are (1) How does the concept of mean scattering cross section (σ_0) apply to a signal with such widespread frequency components? and (2) How does the size of the cell relate to the statistical variations of the scattered signal? A related question to this latter aspect is How do the sidelobe scattering contributions affect the result as the mainbeam resolution cell becomes reduced?

The Panel's recommendations are that a study of the frequency-dependent cross section be investigated for UWB applications. The work should include an investigation of the relation of cell length (and width) on the clutter statistics. The study should include the appropriate dependence on center frequency and the formalism for computing the total clutter power contributions from the mainbeam and sidelobes of the antenna system. This latter aspect will require a specification of the space/time pattern characterization of the antenna system. The investigation should *focus* on short-range applications, foliage penetration, and sea skimmer detection.

Since the theoretical approaches are complex and speculative, some limited experimental effort should be undertaken to confirm the predicted behavior. This *should not* be a broad measurement program with clutter characterization objectives, but a *strictly* limited effort.

IXC. Space/Time Antenna Pattern Characterization for UWB Systems

A key element in the overall performance of a radar system is the antenna beam pattern. For monochromatic systems, the pattern is expressed as an angular distribution of average power density in the far field, and is straightforwardly related to the spatial distribution of current used to excite the antenna via a Fourier transformation. Any signal modulation will not significantly change this pattern, so long as it meets certain requirements which collectively can be called narrowband conditions. Because the modulation is responsible for range resolution, a narrowband antenna pattern is decoupled in angle and range (or space and time).

Ultra-wideband signals and antennas, specifically those that do not meet the narrowband conditions, result in significantly different behavior in the antenna radiation. The fundamental pattern measure itself must be redefined from average power density to integrated energy density, where the integration occurs over a finite time interval associated with a filter (typically matched to the received waveform) in the receiver. The integration time must be finite if the range resolution associated with the signal bandwidth (or duration) is to be realized.

Both UWB antenna elements and antenna array characteristics need to be further understood at the engineering level to provide the tools needed to pursue potential UWB radar applications. The properties of antenna element structures themselves are to be analyzed as part of the Source/Transmitter Design study recommended in Section IXD. The focus here will be on the unique properties of UWB antenna arrays.

For example, effects such as array dispersion and spatial undersampling at high frequencies (spacing > wavelength/2) can result in significantly non-intuitive antenna pattern characteristics, all of which couple the range and angle, and hence space and time, behavior of the antenna response. Consequently, the return from point targets and distributed clutter must be separately and carefully treated. These considerations have led to suggestions that ultra-wideband arrays offer the potential for improved performance in terms of mainlobe width, sidelobe level, element density, and even non-diffracting beams (focus wave modes).

It is therefore recommended that a study be conducted to develop the proper engineering analyses and numerical techniques to characterize the range and angle patterns of ultra-wideband linear and planar antenna arrays. Specific topics which are known to impact performance and should be addressed include

(1) The effects of regular and irregular array element spacing

(2) The effects of waveform shape and bandwidth

(3) The impact of different spectral excitation of each element and its relationship to focus wave modes, EM "bullets", "missiles", etc.

(4) The response to homogeneous, spatially uncorrelated clutter, *vis-a-vis* point targets

(5) The variation of range resolution/response versus angle.

Both general formulas and specific numerical results for representative waveforms and array geometries should be generated. Comparisons to the corresponding narrowband patterns in terms of mainlobe width, sidelobe level, and element density should be performed.

The principal output of this study should be a set of engineering trade-offs between the various parameters discussed above that can be used in radar system design. Recommendations for use of the unique and/or advantageous features of these arrays in radar system applications such as those identified in Section IXA should be made. It is anticipated that this study will require approximately one person-year of effort.

IXD. Impulse Radar Transmitters (Sources and Antennas)

Transmitters for impulse radar are significantly different from those for conventional radar or for spread-spectrum, ultra-wideband radar. Developments in sources and antenna structures suitable for impulse radars have come largely from communities other than the conventional radar community. For example, the development of sources able to produce short-duration high-power pulses has been driven by programs in fusion energy, electromagnetic pulse (EMP) testing, nuclear-weapon diagnostics, directed-energy weapons, etc. Antenna structures suitable for short-duration transients have primarily been developed by programs in EMP testing, ground-penetrating radar, and transient upset high power microwaves (HPM).

Impulse radar sources for short-range applications generally require peak powers and pulse durations that are easily achievable with existing technology. For medium-range and long-range applications, however, total peak powers of well over 100 MW and sub-nanosecond pulse durations are required, as well as average powers comparable to conventional radars. Several presentations before the Panel indicated that new technology sources offer "wall plug to RF" efficiencies in the range of 35 to 50 percent. Only recently have these requirements been deemed feasible; however, issues such as practicality and efficiency remain to be critically evaluated.

The UWB Panel was presented with only a limited view of the wide range of potential source technologies for impulse radar. The continued development of potential impulse radar source technologies such as photoconductors, bulk-avalanche-semiconductor switches, magnetic pulse compression, electromagnetic shock lines, fast thyratrons, etc., can be expected; however, the results may not be optimized for impulse radar applications. Therefore, one possible goal of a funded program in impulse radar would be to critically and thoroughly evaluate the wide range of potential source technologies. Presentations made before the Panel indicate that advances made in switch technology have potential for application in non-impulse UWB and conventional transmitters.

Proven antenna structures suitable for impulse radar applications are primarily traveling-wave structures. A wide degree of variation exists in the detailed realization of these structures, and very little evidence is seen of a fundamental understanding or optimization of these structures. Useful literature presenting engineering design information is also lacking. Given the adequate capabilities for time-domain electromagnetic modeling that are currently available, a careful analysis of the characteristics of antenna structures suitable for impulse radar is feasible. A carefully defined program to evaluate and provide a fundamental understanding of such antenna structures is called for.

IXE. Materials Interactions

There have been vigorous discussions on the effectiveness of impulse radar systems to exploit material phenomena, such as relaxation time and precursors, to aid in the detection of low-observable targets. The reason for the discussions is the assertion[1] that, for sufficiently short pulses, the response of a material is fundamentally different than the response to steady-state signals. This assertion questions the applicability of Fourier transform theory and linear system theory and whether or not swept frequency measurements can be used to duplicate the Fourier components of the short pulse in linear media. This idea is counter to all conventional electromagnetic principles, and, after serious deliberation, the Panel recommends against any system studies based upon unsubstantiated materials phenomena. The choice of impulse versus conventional wideband approaches to radar systems is one of design, rather than fundamental physics, and the Panel has seen no convincing materials evidence to the contrary.

While numerous non-linear effects have been observed by microwave spectroscopists (primarily in gases at low temperatures and pressures), the field intensities required were deemed to be impractical at the ranges of interest for radar systems. The Panel does, however, recommend that the DoD sponsor a modest effort to document the characteristics of self induced transparency relevant to their possible contributions to military systems. This work could be accomplished as part of the JASONS' 1990 Summer Study, a National Science Foundation effort, or funded University research.

---

[1]Barrett, T. W., "Energy Transfer and Propagation and the Dielectrics of Materials: Transient Versus Steady State Effects", 1990, unpublished.

APPENDIX A

TERMS OF REFERENCE, PANEL MEMBERS, OBSERVERS, PRESENTERS, AND MEETING AGENDAS

ULTRA-WIDEBAND RADAR REVIEW PANEL

TERMS OF REFERENCE

1. Review what has been done in ultra-wideband radar development
   a. Available experimental data
   b. Literature, including Soviet unclassified, as available.
2. Review what is being done and what is proposed to be done
   a. Government laboratories, including DOE labs
   b. Industry and academe.
3. Determine potential performance benefits
   a. Radar technology for a variety of applications, including potential for low observable targets
   b. Countermeasures.
4. Identify technology issues and gaps in knowledge, and priority of importance.
5. Recommend research which should be pursued to resolve issues
   a. Areas for further investigation
   b. Experimental tools/hardware needed.
6. Determine possible applications.

ULTRA-WIDEBAND REVIEW PANEL
PANEL MEMBERS

*Denotes Alternate

ELI BROOKNER
RAYTHEON
430 Boston Rd.
M/S B22
Wayland, MA 01778
W(508) 440-5636

JOHN CASHEN
NORTHROP
8900 Washington Blvd.
Pico Rivera, CA 90660-3783
W(213) 948-8985

GEORGE COOPER
CONSULTANT/GENERAL DYNAMICS-POMONA
4461 Glen Way
Claremont, CA 91711
W(714) 868-4891

JIM CORUM
BATTELLE
505 King Avenue
Room 4-133C
Columbus, OH 43201-0693
W(614) 424-3574

CURT DAVIS
LINCOLN LABS
P.O. Box 73, C490
244 Wood St.
Lexington, MA 02173
W(617) 981-7455

BERT FOWLER
CONSULTANT
15 Woodberry Rd.
Sudbury, MA 01776
W(508) 443-7509

ARCHIE GOLD
SAIC
1555 Wilson Blvd.
Suite 700
Arlington, VA 22209
W(703) 525-8585

EVAN IVERSON
LANL
P.O. Box 1663
M/S J580
Los Alamos, NM 87545
W(505) 667-0650

DAVE KRAMER
MITRE
Burlington Rd.
M/S A395
Bedford, MA 01730
W(617) 271-3672

IVAN LAHAIE *
ERIM
P.O. Box 8618
Ann Arbor, MI 48107
W(313) 994-1200, Ext 2217

JAY LOOMIS
MICOM
Cdr, US Army MICOM
ATTN: AMSMI-RD-AS-RA/Dr. Loomis
Redstone Arsenal, AL 35898-5253
W(205) 876-5017

LARRY LYNN
ATLANTIC AEROSPACE
ELECTRONICS CORP
6404 Ivy Ln.
Suite 300
Greenbelt, MD 20770
W(301) 982-5255

ROGER MANASSE
CONSULTANT
234 Canon Drive
Santa Barbara, CA 93105
W(818) 887-4299

ED MILLER
LANL
P.O. Box 1663
MEE-3, M/S J580
Los Alamos, NM 87545
W(505) 667-6249

DENNIS MURRAY
SAIC
3601 Aviation Blvd.
Suite 3600
Manhattan Beach, CA 90266
W(213) 536-0688

FRED NATHANSON
GTRI
11400 Dorchester Ln.
Rockville, MD 20852
W(301) 770-0752

DAVE NELSON
HARVARD/JASON
Lyman Laboratory of Physics
Harvard University
Cambridge, MA 02138
W(617) 495-4331

RICHARD NORTON *
R.J. Norton Company
21290 West Hillside Dr.
Topanga, CA 90290
W(213) 455-1138

ALAN PETERSON
STANFORD UNIVERSITY
227 Durand Bldg
Electrical Engineering
Stanford, CA 94305-4055
W(415) 723-3594

LEE POIRIER *
RADC/EEC
Rome Air Development Center
Electromagnetics Division
Hanscom AFB, MA 01731-5000
W(617) 377-2526

JIM RALSTON
IDA
1801 N. Beauregard Street
Alexandria, VA 22311
W(703) 578-2823

STAN ROBINSON
ERIM
P.O. BOx 8618
Ann Arbor, MI 48107
W(313) 994-1200, Ext 2505

JAY SCHINDLER
RADC/EE
Rome Air Development Center
Electromagnetics Division
Hanscom AFB, MA 01731-5000
W(617) 377-3700

MERRILL SKOLNIK
NAVAL RESEARCH
LABORATORY
455 Overlook Ave. S.W.
Code 5300
Washington, DC 20375-5000
W(202) 767-2936

NICK TOMLJANOVICH *
MITRE
Burlington Rd.
M/S A395
Bedford, MA 01730
W(617) 271-5564

ULTRA-WIDEBAND REVIEW PANEL
OBSERVERS

GREGORY V. CIRINCIONE
SAIC
1555 Wilson Blvd.
Suite 700
Arlington, VA 22209
W(703) 525-8585

COL BARRY CRANE
ODDRE (R&AT/ET)
ATTN: COL Crane
Room 3D1089
The Pentagon
Washington, DC 20301-3080
W(202) 695-0005

JOHN DAVID
HARRY DIAMOND
LABORATORIES
Department of the Army
Harry Diamond Laboratories
ATTN: SLCHD-ST-R/John David
2800 Powder Mill Road
Adelphi, MD 20783
W(202) 394-2530

JOHN N. ENTZMINGER
DARPA/TTO
1400 Wilson Blvd.
Arlington, VA 22209
(703) 694-2440

DOMINICK GIGLIO
DARPA/TTO
1400 Wilson Blvd.
Arlington, VA 22209
W(703) 694-8232

BRENDON GODFREY
(505) 844-9856

PETE HOAG
JCLO Office
1215 Jefferson Davis Highway
Room 1208
Arlington, VA 22202
W(202) 692-5675

JIM HOGARTY
JCLO Office
1215 Jefferson Davis Highway
Room 1208
Arlington, VA 22202
W(202) 692-5675

BERT HUI
DARPA/DSO
1400 Wilson Blvd.
Arlington, VA 22209
W(703) 694-2440

JOHN MCCORKLE
HARRY DIAMOND LABORATORIES
Department of the Army
ATTN: John McCorkle
2800 Powder Mill Road
Adelphi, MD 20783
W(202) 394-2530

RICHARD MUIR
NAVSEA
Commander
Naval Sea Systems Command
Department of the Navy
Washington, DC 20362-5101
W(703) 437-7516

ART PAVEL
DARPA/AVSTO
1400 Wilson Blvd.
Arlington, VA 22209
W(202) 694-1893

VINCENT PUGLIELLI
BATTELLE
505 King Avenue
Room 4-1-33E
Columbus, OH 43201-2693
W(614) 424-7319

GEORGE T. RUCK
BATTELLE
505 King Avenue
Room 4-1-33B
Columbus, OH 43201-2693
W(614) 424-5685

RAY SIEWART
ODDRE (R&AT/ET)
ATTN: Mr. Siewart
Room 3D1089
The Pentagon
Washington, DC 20301-3080
W(703) 697-7922

PHILIP L. SOUCY
SAF/AQ
Department of the Air Force
ATTN: SAF/AQ
Washington, DC 20330-1000

FRANK E. WELKER
USAF/RADC
Griffiss Air Force Base, NY 13441-5700
W(315) 330-4437

MIKE WICKS
RADC/OCT
Griffiss Air Force Base, NY 13441-5700
W(315) 330-4437

ROBERT WILLIAMS
DARPA/DIRO
1400 Wilson Blvd.
Arlington, VA 22309
W(703) 694-2564

ELI ZIMET
OFFICE OF NAVAL TECHNOLOGY
800 N. Quincy St.
Arlington, VA 22217-5000
W(202) 696-4771

ULTRA-WIDEBAND REVIEW PANEL
PRESENTERS

M. SKOLNIK
NRL

M. WICKS
RADC

C. DAVIS
LINCOLN LABS

D. KRAMER
MITRE

E. THOMPSON
DIA

J. COLEMAN
DIA

B. CRANE
U.S. ARMY

V. PUSATARI
NOSC

L. FULLERTON
TIME DOMAIN SYSTEMS

J. MCCORKLE
HDL

J. CORUM
BATTELLE

H. HARMUTH
CU

T. JOHNSON
BOEING

T BARRETT
BOEING

S. DAVIS
POWER SPECTRA

W. HAPPER
JASON

C. PHILLIPS
THERMO-ELECTRON

D. SULLIVAN
MRC

L. FRAZIER
GENERAL DYNAMICS

R. VICKERS
SRI

G. ROSS
ANRO

F. ZUCKER
RADC

A. SCHUTZ
GSSI

R. MOREY
GSSI

J. P. HANSEN
NRL

J. YOUNG
OHIO STATE U.

R. HUTCHINS
BDM

W. PEARSON
MCDONNELL DOUGLAS

G. COOPER
GENERAL DYNAMICS

S. PENG
TELEDYNE RYAN ELECTRONICS

D. MILLER
U. OF ROCHESTER

K. OUGSTON
U. OF VERMONT

M. FRIEDMAN
NORTHEASTERN U.

B. WILLIAMS
DARPA

M. VAN BLARICUM
TOYON

T. SARKAR
SYRACUSE U.

AGENDA

ULTRA-WIDEBAND STUDY - SESSION 1

February 22, 1990

0830-0840	Welcome & Introduction	B. Tullington
0840-0900	Study Objective & General Discussion	C.A. Fowler
0900-1000	NRL Activities	M. Skolnik
1000-1015	Break	
1015-1115	RADC/OCT Program Review	M. Wicks
1115-1215	Lincoln Lab/RADC/MITRE Study	L. Pourier/ C. Davis
1215-1315	Working Lunch/Panel Discussion	
1315-1445	DIA	Ed Thompson/ J. Coleman
1445-1500	Break	
1500-1700	Panel Discussion	C.A. Fowler/ Jim Corum
1700	Meeting Adjourned	

ULTRA-WIDEBAND STUDY

AGENDA

March 20, 1990

SPC Conference Room
1500 Wilson Boulevard
Arlington, VA 22209

Times	Subject	Presenter
0830 - 0840	Welcome	B. Tullington, Battelle
0840 - 0915	Chairman's Remarks	C. Fowler
0915 - 1015	Current UWB Projects	B. Crane, USA
1015 - 1030	Break	
1030 - 1130	NOSC UWB Programs	V. Pusatari, NOSC
1130 - 1230	Working Lunch	
1230 - 1330	UWB Experimental Results	L. Fullerton, Time Domain Systems
1330 - 1430	Foliage Penetration UWB SAR	J. McCorkle, HDL
1430 - 1450	Break	
1450 - 1550	Review of Los Alamos UWB Conference	J. Corum, Battelle
1530 - 1700	Panel Discussion	C. Fowler/ J. Corum, Battelle
1700	Chairman's Remarks & Adjournment	C. Fowler

ULTRA-WIDEBAND STUDY

AGENDA

March 28,1990

SAIC Conference Room
1555 Wilson Boulevard
Suite 700
Arlington, VA 22209

Times	Subject	Presenter
0830 - 0840	Welcome	B. Tullington, Battelle
0840 - 0900	Chairman's Remarks	C. Fowler
0900 - 1000	General Principles of UWB	H. Harmuth, CU
1000 - 1020	Boeing Company Programs, Introduction	T. Johnson, Boeing
1020 - 1040	Break	
1040 - 1140	Theoretical Approach to UWB Radar	T. Barrett, Boeing
1140 - 1210	Working Lunch	
1210 - 1310	Near-term UWB Applications	S. Davis, Power Spectra
1310 - 1510	UWB Applications	H. Harmuth, CU
1510 - 1530	Break	
1530 - 1630	Analysis of Impulse Radar and Materials Effects	W. Happer, JASONS
1630 - 1700	Panel Discussion	C. Fowler, J. Corum Battelle
1700	Chairman's Remarks & Adjournment	C. Fowler

ULTRA-WIDEBAND STUDY

AGENDA

March 29, 1990

SAIC Conference Room
1555 Wilson Boulevard
Suite 700
Arlington, VA 22209

Times	Subject	Presenter
0830 - 0840	Welcome	B. Tullington, Battelle
0840 - 0900	Chairman's Remarks	C. Fowler
0900 - 1000	Panel Discussion	C.Fowler/ J. Corum, Battelle
1000 - 1020	Break	
1020 - 1120	Application of UWB for Radar	C. Phillips, Thermo-Electron
1120 - 1200	Working Lunch	
1200 - 1300	UWB Weapon Applications	D. Sullivan, MRC
1300 - 1400	UWB Weapon Applications	L. Frazier, GD
1400 - 1420	Break	
1420 - 1520	UWB Aircraft Signatures	R. Vickers, SRI
1530 - 1700	Panel Discussion	C. Fowler/ J. Corum Battelle
1700	Chairman's Remarks & Adjournment	C. Fowler

ULTRA-WIDEBAND STUDY

AGENDA

April 4, 1990

SPC Conference Room
1500 Wilson Boulevard
Arlington, VA 22209

Times	Subject	Presenter
0830 - 0840	Welcome	B. Tullington, Battelle
0840 - 0900	Chairman's Remarks	C. Fowler
0900 - 1000	UWB Applications	G. Ross, ANRO
1000 - 1020	Break	
1020 - 1120	Fundamental Issues	F. Zucker, RADC
1120 - 1200	Working Lunch	
1200 - 1300	Impulse Radar	A. Schutz, GSSI
1300 - 1400	UWB Technologies	R. Morey, GSSI
1400 - 1420	Break	
1420 - 1520	Absorber Measuring Contrasting UWB Instantaneous Swept Frequency Techniques	J.P. Hansen, NRL
1520 - 1620	UWB Diagnostic Target Imaging	J. Young, OSU
1620 - 1700	Panel Discussion	C. Fowler/J. Corum
1700	Chairman's Remarks & Adjournment	C. Fowler

ULTRA-WIDEBAND STUDY

AGENDA

April 5, 1990

SPC Conference Room
1500 Wilson Boulevard
Arlington, VA 22209

Times	Subject	Presenter
0830 - 0900	Welcome/Chairman's Remarks	B. Tullington, Battelle/C. Fowler
0900 - 1000	Impulse Radar Clutter Models	J. Copeland, BDM
1000 - 1015	Break	
1015 - 1115	Low Observables	W. Pearson, McDonnell Douglas
1115 - 1215	Noise Radar & Working Lunch	G. Cooper
1215 - 1700	Panel Discussion	C. Fowler/J. Corum
1700	Adjournment	C. Fowler

DoD/DARPA BTI Committee Review of Boeing Aerospace Electronics
Energy Crafting for Optimum Propagation (ECOP) Concept
(Energy Propagation Technology)

April 24, 1990

The Boeing Company
Rosslyn Center, 20th & 21st Floors
1700 North Moore Street
Rosslyn, VA 22209
(703) 558-9600

8:30-8:35	Introduction & Overview (J. B. Walsh, Boeing A&E, VP R&E)
8:35-9:00	Summary of Energy Crafting for Optimum Propagation (ECOP) Concept (Terence Barrett, Boeing A&B)
9:00-10:00	First Proposition of ECOP, addressing 70% of effort (Terence Barrett): The optimum emitted signal is that which is matched, filtered, (in both frequency and time), to the medium, target shape and material, and the desired results (Matched Filtering Adaptive Reconfigurable Array)
10:00-10:30	Discussion & Questions
10:30-10:45	Break
10:45-11:15	Teledyne Ryan Electronics (Sheng Peng): Adaptive Reconfigurable Timed Array
11:15-12:15	General Dynamics (Larry Frazier): Side-Looking Imaging Radar
12:15-12:30	Lunch (Catered Working Lunch)
12:30-13:30	Power Spectra Inc. (Steve Davis): Bulk Avalanche Semiconductor Switch
13:30-13:45	Testing of Interceptor Hardware (Don Simms or Ed Trou, Boeing A&E)
13:45-14:00	Break
14:00-15:00	Second Proposition of ECOP, addressing 30% of effort (Terence Barrett): The Dielectric response of media to transient signals of sufficiently short duration is distinctly different from the dielectric response to steady state signals. (Radiation Matter Interactions).
15:00-15:15	Discussion & Questions
15:15-15:30	Break
15:30-16:00	University of Rochester (Dwayne Miller): Dielectric effects with transient signals
16:00-16:30	University of Vermont (Kurt Ougston): Precursor effects of radar frequencies
16:30-17:00	Northeastern University (Marvin Friedman): Advanced electromagnetic theory
17:00-17:15	Potential Applications Spectrum of UWB
17:15-17:30	Summary of ECOP COncept: Propositions #1 & #2
17:30-17:45	Recommendations for BTI/Other Government Support of UWB Activities
17:45-18:00	Discussion & Questions
18:00-18:30	Committee Deliberations
18:30	END

ULTRA-WIDEBAND
SUB-PANEL ATTENDANCE LIST

April 24, 1990
(GOVERNMENT ONLY)

NAME	AFFILIATION
CORUM, JAMES F.	BATTELLE
ENTZMINGER, JOHN	DARPA
HOAG, PETER	JCLO
HOGARTY, JIM	JCLO
IVERSON, EVAN	LANL
LOOMIS, JAY	MICOM
MUIR, RICHARD	NAVSEA
POIRIER, LEE	RADC
PUGLIELLI, VINCENT G.	BATTELLE
RALSTON, JAMES	IDA
RUCK, GEORGE T.	BATTELLE
SCHINDLER, JAY	RADC
SKOLNIK, MERRILL	NRL
SOUCY, PHILIP	SAF/AQ
TULLINGTON, BERNIE	BATTELLE
WILLIAMS, ROBERT	DARPA
OLIVER, MARION	JHU/APL
HUI, BERTRAM	DARPA
MCCORKLE, JOHN	HDL

ULTRA-WIDEBAND STUDY

AGENDA

April 25, 26, 1990

BATTELLE CONFERENCE ROOM
1300 N. 17th Street, Suite 1520
Arlington, VA 22209
Telephone, (703) 875-3340

Times	Subject	Presenter
	APRIL 25, 1990 - SUB PANEL MEETING	
1000 - 1005	Welcome, Sub-Panel	B. Tullington, Battelle
1005 - 1015	Remarks	J. Entzminger, DARPA
1015 - 1200	Sub Panel Discussions & Conclusions from Boeing Session	J. Entzminger/J. Corum
1200 - 1345	Lunch Break	
	APRIL 25, 1990 - FULL PANEL MEETING	
1345 - 1400	Opening Remarks, Full Panel	C. Fowler
1400 - 1450	Systems Aspects of Resonance-Based Target Identification	M. VanBlaricum, Toyon
1450 - 1500	Break	
1500 - 1550	Conventional LaPlace Transient EM Issues	T. Sarkar, Syracuse
1550 - 1630	Sub Panel Report on Boeing Session	J. Entzminger/J. Corum
1630 - 1700	Panel Discussions	C. Fowler/J. Corum
1700	Chairman's Remarks & Adjournment	C. Fowler

APRIL 26, 1990 - FULL PANEL MEETING

0830 - 0845	Opening Remarks	C. Fowler
0845 - 1700	Panel Discussions & Reports	C. Fowler
1200 - 1245	Working Lunch	
1700	Chairman's Remarks & Adjournment	C. Fowler

ULTRA-WIDEBAND STUDY

AGENDA

June 14, 1990

BATTELLE CONFERENCE ROOM
1300 N. 17th Street, Suite 1520
Arlington, VA 22209
Telephone, (703) 875-3340

Times	Subject	Presenter
0830 - 0845	Welcome/Chairman's Remarks	C. Fowler
0845 - 0900	Draft Report Organization and General Comments	J. Corum, Battelle
0900 - 1700	Final Report Discussion	C. Fowler
1200 - 1245	Working Lunch	
1700	Closing Remarks	C. Fowler

250 East River Road
Rochester, New York 14623

Laboratory for Laser Energetics

TEL 716 275 5101

Agenda

Ultrawide Band Radar Panel Site Visit

Friday, 11 May 1990

11:30	Tour of Facilities at the Laboratory for Laser Energetics	Dwayne Miller Sam Letzring William Dc naldson
12:30	Lunch on Site	
13:00	Short Pulse Effects in the Optical Regime	Joseph Eberly
14:00	Experimental Observation of Short Pulse Effects.Outline of Experimental Program	Dwayne Miller
15:00	High Power Photoconductive Switching for Microwave Pulse Generation	William Donaldson
16:00	Summary 'eeting Adjourned	

ULTRA-WIDEBAND SUB-PANEL
ATTENDANCE LIST

May 11, 1990

University of Rochester

NAME	AFFILIATION
JAMES RALSTON	IDA
MERRILL SKOLNIK	NRL
GEORGE RUCK	BATTELLE
VINCE PUGLIELLI	BATTELLE
JAMES CORUM	BATTELLE

APPENDIX B

CALCULATIONS AND ANALYSES FOR IMPULSE RADAR

APPENDIX B

CALLOCATIONS AND ANALYSES FOR IMPULSE RADAR

PART I[1]

This Appendix presents the results of a few sample calculations in order to illustrate some of the characteristics of impulse radar. No claim for mathematical rigor is made, as these results are intended primarily to yield insight into some of the aspects of impulse radar that differ from those familiar to the conventional radar practitioner. However, it is believed that all of the results presented here can be made rigorous with little or no change in the major conclusions reached.

Pulse Description

In order to present some quantitative results, it is necessary to describe the transmitted signal. This is most conveniently done by defining the antenna current, realizing that the far-zone electric field is proportional to the time-derivative of this current. In order to satisfy physical requirements, it is necessary that the antenna current and its derivative both be zero at the initial instant. This results in a transmitted signal that is more realistic than some that have been discussed in the literature. The specific form that has been considered here is

$$i(t) = I_0(t/T)^2 \exp(-2t/T) \tag{1}$$

where T is defined to be the rise time of the current pulse, i.e., the time at which the first current maximum occurs. Note that T will also be the time to

[1]Contributed by George Cooper - Consultant/General Dynamics-Pomona. This appendix was condensed by the author from Appendix B of Los Alamos Report LA-UR-89-1420, 5 June 1989.

the first zero-crossing of the radiated electric field. The antenna current and its derivative are displayed in Figure B-1. Other forms of antenna current can also be considered, but the results are not radically different.

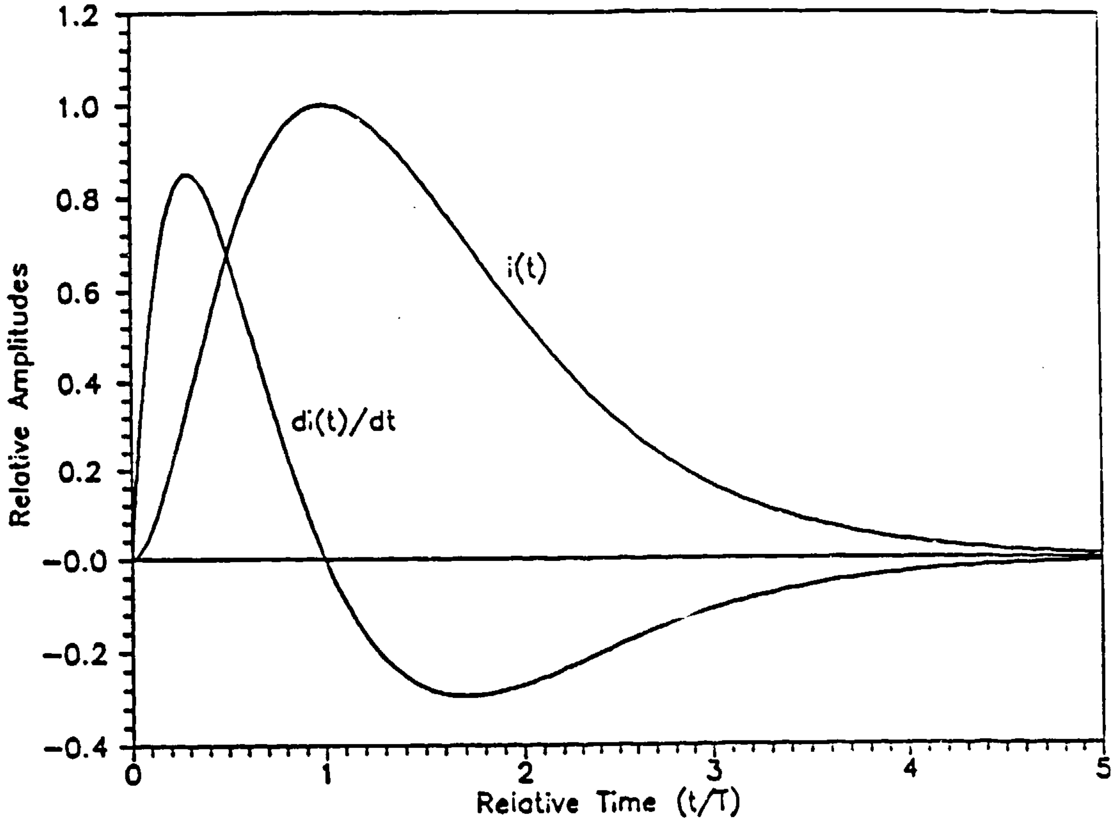


FIGURE B-1. ASSUMED ANTENNA CURRENT PULSE AND ITS FIRST DERIVATIVE

Radar Range Equation[1]

One of the most basic results in conventional radar is the equation that predicts the maximum range at which targets can be detected. A similar result can be obtained for impulse radar. The development of this result starts with the conventional equation that relates the received energy per pulse to the transmitted energy per pulse. This is

$$E_R = \frac{E_T G_T A_R \sigma}{(4\pi)^2 R^4 L} \tag{2}$$

where[2]

E_R = Received energy per pulse
E_T = Transmitted energy per pulse
G_T = Gain of the transmitting antenna
A_R = Effective area of the receiving antenna
σ = Cross-section of a target reflecting point
R = Range
L = Total system loss.

Note that this is not consistent with IEEE definitions.

For impulse radar, the antenna gain G_T is the ratio of the maximum spatial energy density (J/m^2) produced by the antenna to the energy density that would be produced by an omnidirectional antenna. The radar cross-section σ is the ratio of the energy per unit solid angle scattered in the direction of the radar to the energy density impinging upon the target.

It has been shown by direct computation that the gain of an array for the impulse radar is very nearly equal to the number of elements in the array. This is most nearly true when the spacing of the elements is one-half of the wavelength associated with the frequency at which the radiated pulse

[1]In this section, gain is defined in terms of total energy via Parseval's Theorem.

[2]Care must be taken when using these quantities, since they are not *spectral* densities and do not correspond to the usual IEEE definitions.

has its spectral maximum, but it does depend also upon the pulse rise time, as discussed in a subsequent section. If the element spacing is taken to be βcT, where β is a constant near unity, and $c = 3 \times 10^8$ m/s, then the gain of the transmitting antenna becomes

$$G_T = \frac{A_T}{(\beta cT)^2} \tag{3}$$

where A_T is the effective area of the transmitting antenna.

The ability to detect a target with a single pulse depends upon the ratio E_R/N_o, where N_o is the one-sided spectral density of the receiver noise. Upon introducing the appropriate value for N_o and solving for the range, the radar range equation becomes

$$R_{max} = \left[\frac{E_T A_T A_R \sigma}{(4\pi\beta cT)^2 (E_R/N_o)(kT_oFL)}\right]^{1/4} \tag{4}$$

where

$kT_o = 4 \times 10^{-21}$

F = Receiver noise figure.

This result is displayed in Figure B-2 for a specific set of parameters. It is worth noting that for a given transmitted pulse energy the maximum detection range <u>increases</u> with <u>smaller</u> pulse rise times. This is because the number of elements in an aperture of given size can be increased for shorter pulses and, hence, the antenna gain is increased. It should also be noted that a sinusoidal signal radar having a wavelength of $\lambda = \sqrt{4\pi \beta}\, cT$ and the same pulse energy would have exactly the same maximum detection range as shown here. Furthermore, the sinusoidal signal would still allow a trade-off between peak power and pulse duration, which the assumed impulse radar signal does not permit. The advantage of the impulse radar is that a given level of performance can be achieved at a lower absolute frequency.

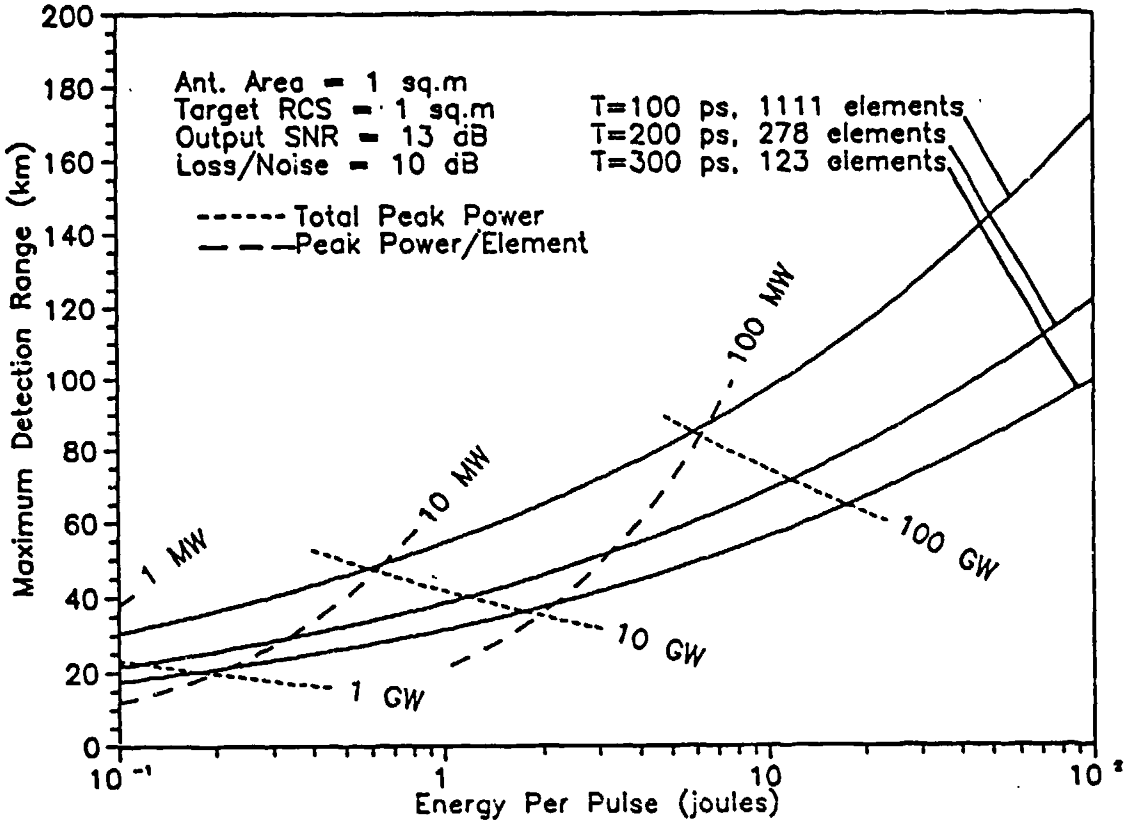


FIGURE B-2. MAXIMUM DETECTION RANGE FOR AN IMPULSE RADAR

Also displayed on Figure B-2 are curves of constant total peak power and curves of peak power per antenna element. These curves demonstrate that extremely large peak powers are required to achieve detection at reasonable ranges. This suggests that integration of pulses is almost unavoidable with impulse radar. Since the limiting factor of existing high-energy pulsers seems to be repetition rate, such integration may be difficult to achive.

Range Resolution

The theoretical range resolution of any radar is defined in terms of the equivalent bandwidth of the radiated signal. This equivalent bandwidth is simply the ratio of the square of the single pulse energy to the integral of the square of the pulse correlation function. For a single parameter pulse (that is, one whose shape is defined completely by its rise time) the general result is that the theoretical range resolution is given by

$$\delta_R = \frac{cT}{2\gamma} \tag{5}$$

where γ is a constant defined by the pulse shape. For the pulse specified above, $\gamma = 4/3$. The practical range resolution, after receiving the signal in a matched filter, will be somewhat larger than δ_R by perhaps 25 percent.

Velocity Resolution

Because of the large fractional bandwidth of the impulse radar signal the concept of a unique doppler shift has little meaning. Thus, the usual technique of measuring target velocity by observing a doppler shift is not viable. However, target velocity can be measured by observing a sequence of M pulses and making a least-squares estimate of velocity from the arrival times of these pulses. The velocity resolution is then related to the range resolution by

$$\delta_V = \frac{\delta_R \text{ (PRF)}}{M} \tag{6}$$

where PRF is the pulse repetition rate.

Multipath Resolution

One of the advantages claimed for impulse radar is an ability to resolve multipath returns from low-altitude targets. One measure of this ability is the ratio of the total energy returned by all four paths to and from a single reflecting point over an ideal flat surface to the energy returned from the direct path only. As is well known, for a sinusoidal radar signal, this ratio varies from a maximum value of 12 dB to periodically-spaced deep nulls located at ranges that depend upon the particular geometry.

It is straightforward to make a similar calculation for the impulse radar signal. The result of such a calculation is displayed in Figure B-3 for the impulse ra r signal defined above. In this figure the abscissa is the range to the target and the ordinate is the ratio of total energy to direct path energy. It may be noted that although the maximum ratio is only on the order of 8 dB (instead of 12 dB) there are no nulls. The range at which substantial signal cancellation begins to occur depends upon the pulse rise time, being larger for shorter pulses as would be expected. Note that the target altitude and radar altitude are typical of what might be expected for a sea skimmer and a shipboard radar.

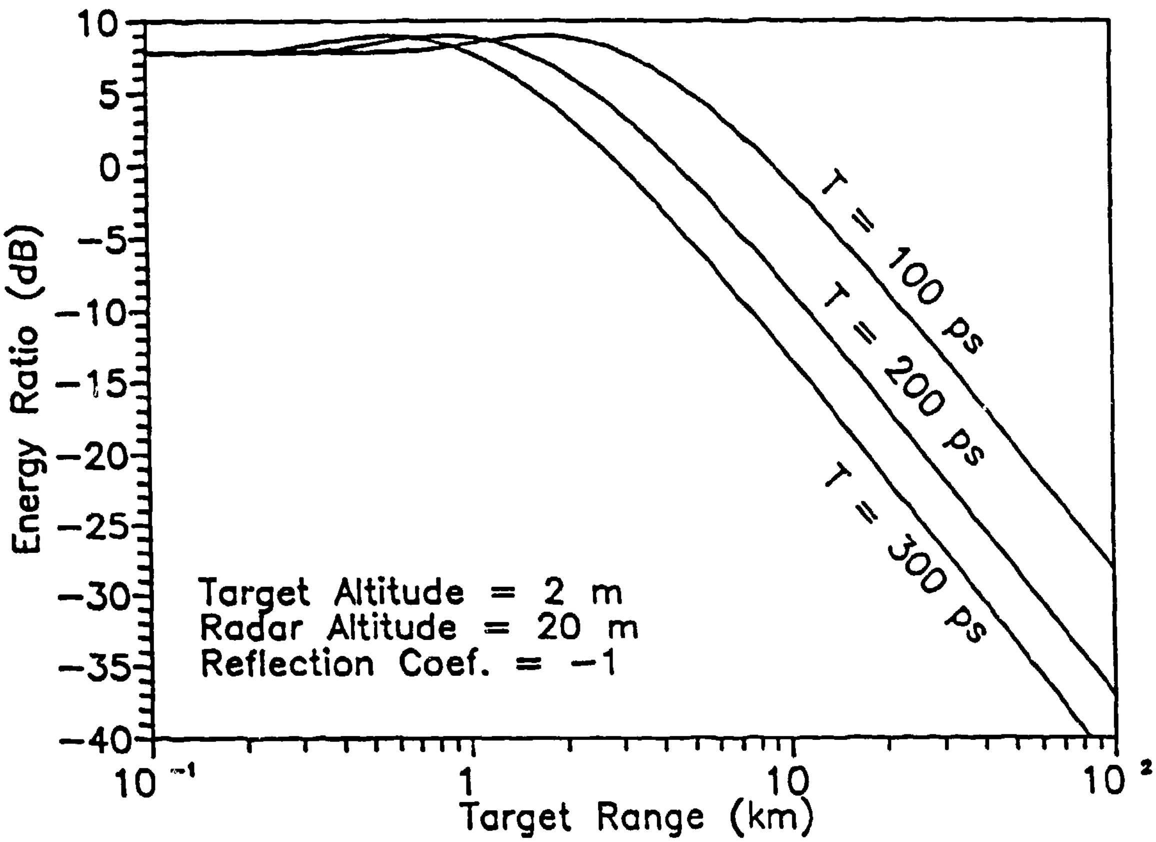


FIGURE B-3. RECEIVED ENERGY RATIO FOR A MULTIPATH SITUATION

Array Antennas For Impulse Radar

A great deal of discussion concerning the performance of arrays with short pulses has developed. There are two basic reasons for this. In the first place, it is believed that the very high peak powers required for many applications of impulse radar can only be achieved by separately exciting the elements of an array. Secondly, wideband radiating structures can be more easily achieved with small radiators than with large dishes or horns. One of the consequences of using an array, however, is that the sidelobe levels cannot be controlled as easily as they can be with sinusoidal signals.

It is a straightforward matter to calculate the radiation pattern and the gain of a linear array of elements. Such a calculation is displayed in Figure B-4 for a 33-element array with uniform excitation. It should be noted that what is plotted is the radiated energy density and not what would be received in a matched filter. Several points are worth noting:

(a) With very short pulses the sidelobe level at large angles increases to approximately one over the number of elements.

(b) The gain of the antenna with respect to isotropic increases as the pulse rise time is made shorter. Although not apparent from this figure, the gain has been shown to be nearly equal to the number of elements when the element spacing is one-half of the wavelength corresponding to the frequency of the radiated signal spectral maximum. For the antenna considered here, the 100 ps rise time approximately fulfills this condition, and the gain should be about 15.2 dB. Gains higher than that can be achieved with even smaller rise times.

(c) The sidelobe level at large angles can be lowered by increasing the pulse rise time, but at the expense of reduced gain and increased beamwidth.

(d) An array intended for impulse radar can null out narrowband interfering signals to exactly the same degree as the same size array intended for narrowband signals. However, the receiving gain of the array for impulse signals may well be degraded.

(e) The array considered here is a filled aperture, although many UWB antenna concepts do not involve filled apertures. The ability of impulse radar to utilize an unfilled aperture is seen as an advantage. Furthermore, it may be difficult, or impossible, to use element spacings as close as shown here. More practical element spacings may be on the order of twice the value assumed here, with a corresponding loss in gain.

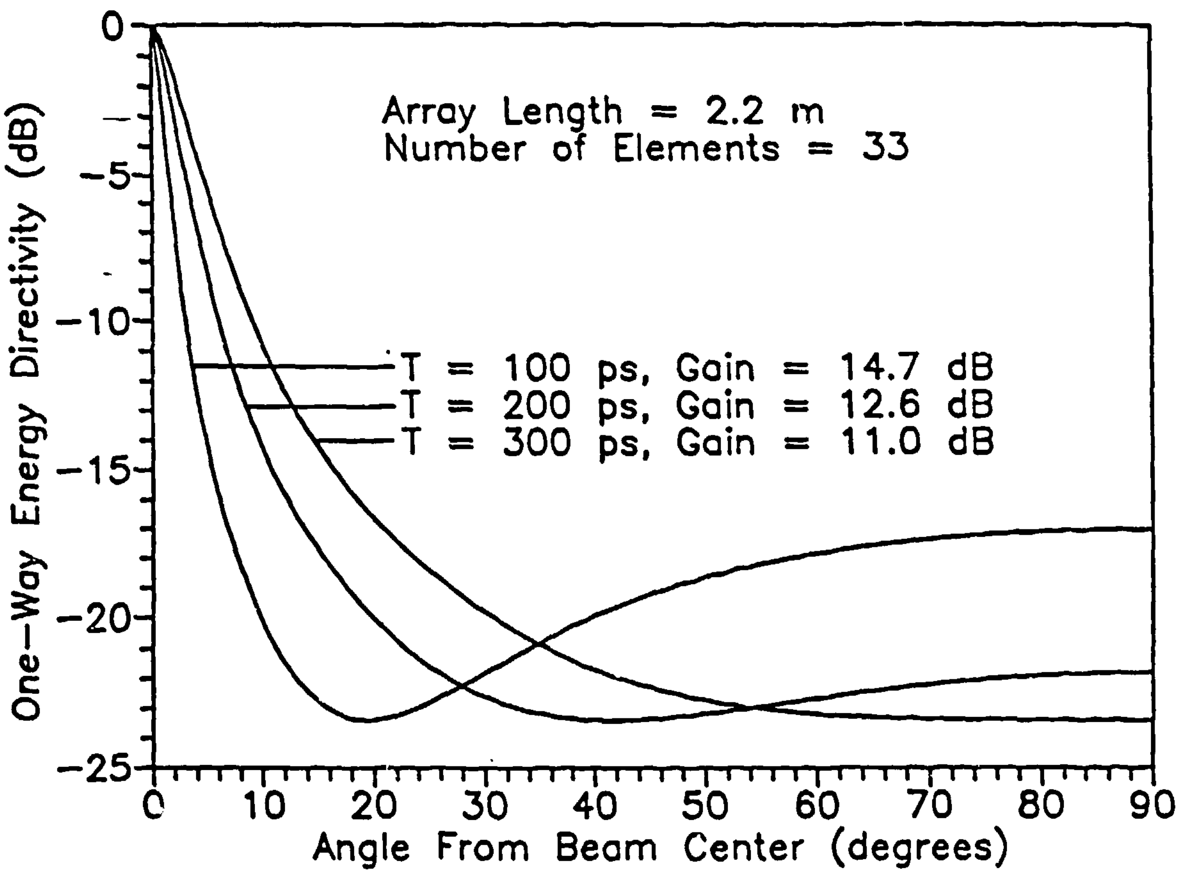


FIGURE B-4. ONE-WAY RADIATION PATTERNS FOR A LINEAR ARRAY WITH UNIFORM EXCITATION

Impulse Radar for Long-Range Detection[1]

The extremely short pulses used in impulse radar lead to a low average power which results in poor target detection performance. It is a radar's average power (or more precisely, energy), and not its peak power, that determines noise limited detection performance. A typical search radar has 1 Joule of energy per pulse and integrates a large number of pulses, further increasing the total energy involved in detection. To increase the signal energy, the UWB waveform designer could use a long coded pulse (which might be implemented as a burst of impulses at a PRF in the megahertz range). In this way the average power problem could be overcome by a brute force application of pulse coding and high peak power. However, if the necessary average power *is* achieved a serious problem ensues: severe interference with the many other military and civil in-band users. These users are normally protected from search radar interference by frequency selectivity, but in this case they are well within the band of the UWB radar. Though the narrowband conventional receiver accepts only a small fraction of the UWB radar's bandwidth, the resulting signal reduction (which can be as much as 60 dB) is still not enough to suppress the interference from a powerful UWB radar. Interference problems, and conversely the susceptibility of the UWB receiver to interference from the other users of the band, will tend to prevent UWB long range detection radars from becoming a practical reality.

---

[1]This section contributed by Curtis W. Davis - MIT/Lincoln Laboratory

PART II[1]

UWB Conversion of a VHF Radar

There has been some speculation on the potential performance gains that could be achieved by adding to a lower-frequency (e.g., VHF) surveillance radar an impulse radar made for non-cooperative target recognition. A reasonable scientific effort would be assumed, but no major reworking of the antenna reflector is considered. This appendix attempts to analyze such an approach. The original feed antenna is assumed here to be replaced by a broadband horn. Without a complete rework of the reflector, the highest frequency of the system is limited to 500 MHz. Usage of this frequency region is dense, and many of the in-band radars might be in close physical proximity. In order to prevent the UWB radar from seriously interfering with other systems within its bandwidth, it could only be pulsed at the precise time the rotating antenna was pointed at the target. (The rotation mechanism of the hypothesized radar does not allow slaved static pointing.) As such, the data collection process would have to be cued in angle by another radar. The UWB radar function would therefore be that of providing target identification or classification. (Limitation to this role is further dictated by the fact that the detection performance of the original long-pulse system is superior to the UWB system, even accounting for multipath loss). Details of the UWB system analysis are given below.

The facility to integrate sequential return pulses from a moving target would greatly complicate the receiver, so a single pulse measurement is assumed. Cueing in range by another radar would further simplify the receiver processing requirements. The bandwidth limitations and practical issues associated with the pulse generator/antenna feed combination lead to the hypothesis of a 2.9-ns pulse with a 9.5-MW peak power.

To perform a reliable identification role, a 20-dB signal-to-noise ratio (SNR) is required. On a conventional cruise-missile-sized targets, this is achieved at a range of 20 km. For fighter-sized targets, this extends out

---

[1]Contributed by Curtis W. Davis - MIT/Lincoln Laboratory

to 36 km. This is a very limited capability. If the SNR requirement were to be reduced to increase the maximum range, identification performance would suffer but the classification of target size might still be possible. However, the range resolution necessary for target size classification could be achieved with a much narrower bandwidth. Therefore, ultra-wide bandwidths are not needed.

If a true ultra-wideband capability is implemented on the hypothesized VHF radar, the existing transmitter and receiver will be of no use. The antenna feed must be changed. This leaves only the reflector. It will be assumed that a major restructuring of the reflector is not involved, since the exercise is to be considered a retrofit, not a new radar development.

The UWB waveform represents a significant interference source to other radars and communications gear within the UWB radar's band. Because of this it will be assumed that the UWB radar will not be pulsed continuously (as it might be for a search function), but will be cued by a separate radar to transmit a pulse or burst of pulses pulse only when the antenna is pointed at a desired target. The azimuth drive on the hypothesized radar only operates in a continuously rotating mode. The slaving of the antenna boresight in fixed directions is not possible without changing the azimuth drive.

The need for cueing suggests that the role of the system would be for target identification or characterization. Detection of the target signal generally requires a signal to noise ratio (SNR) of 10 dB (the signal amplitude is 3 standard deviations, $3\sigma_n$, above the rms noise amplitude). For the identification role proposed here, the required SNR will be higher.

In identification schemes, there is a distinction between the SNR required for the developing the training set (30 dB or better) and that required for reasonable performance. It will be assumed here that a 20 dB SNR (signal amplitude is $10\sigma_n$) will be required for operation (and that the initial training set is obtained from model measurements). This incurs a range reduction by a factor of 0.6 from the range at which the target would simply be detected.

The Targets

The target scattering characteristics have an important influence on the radar performance. We will consider a conventional cruise missile and a conventional fighter class target. Each target will be (arbitrarily) considered to have a radar cross section that is constant with frequency. A more stressing case, which is not considered here, involves targets with radar cross sections that fall off as $1/f^2$.

The Transmit Pulse

Practical triggerable pulse generators using semiconductor technology generally cannot deliver more than 20,000 volts to a load. This value will be used for the present analysis. Higher voltages would probably lead to breakdown problems in the transmission line and antenna feed structures[1].

It will be assumed that the UWB pulse generator will deliver a half-cosine voltage pulse to a 42-ohm input surge impedance of the feed horn, and that the maximum bandwidth obtainable with this waveshape will be sought. Given the upper bound of 500 Mhz (from the next section), this results in a 2.9-nS pulse. Based on the pulse generation technology and voltage breakdown considerations, a 20,000-volt peak amplitude will be used. This pulse has a peak power of 9.5 MW and a total energy of 13.8 mJ. The feed horn will differentiate the pulse so the radiated waveform will be a 2.9-nS monocycle (a single sine cycle), which has a spectrum spanning from 190 to 500 Mhz (3 dB points).

[1]Up to 200,000 volts can be obtained with certain spark discharge devices (such as a Marx generator, a voltage multiplier that charges capacitors in parallel and discharges them in series). The pulses developed by these devices are poorly shaped for radar applications (much ringing), the rise times are too slow, and the pulse widths are too long for the application proposed here.

The Antenna

The reflector portion of the VHF radar antenna places an upper limit on the useable frequency. The reflector is assumed to be made of 16-gauge wires strung horizontally with a 10-cm spacing. The reflection coefficient supported by the reflector mesh begins to fall off rapidly above 500 MHz [1]. In addition, though the precision of the paraboloid is acceptable at the original operating frequency, reflector geometry imperfections will impart pulse timing errors on the order of 0.5 nS to the transmitted signal, affecting the useable gain and range resolution.

The feed for the reflector will be changed to a broadband horn. The lowest frequency will be nominally set at 190 MHz, which is close to the frequency of the original system. The feed pattern at 190 MHz will be set optimally for the reflector. The nature of the horn as an aperture antenna results in an increase in feed gain as the signal frequency increases, coupled with a narrowing of the feed beamwidth. This reduces the effective area of the reflector. The net result is that the overall antenna gain (and beamwidth) is held relatively constant with frequency.

Incorporating a feed horn efficiency of 50 percent, the overall gain of the antenna is G_t=30 dB. The transmit gain and effective receive aperture area of an antenna are related by the following equation:

$$A_r = \lambda^2 G_t / 4\pi \tag{7}$$

If A_1 is defined as the effective aperture at frequency f_1, Equation (7) can be rewritten as:

$$A_r = A_1 (f_1/f)^2 \tag{8}$$

For the subsequent analysis f_1=190 MHz and A_1=198 m^2.

The Receiver

Target identification from a single pulse is assumed. Integration of consecutive return pulses from a moving target is possible, but at a great increase in complexity to the receiver/processor. The target returns will move several tens of range cells over the integration period, requiring an integration process tuned to the specific target range-rate. Note also that the range and range-rate estimates from cueing sensors would be much coarser than the precision required to isolate a target cell in the UWB receiver, so a large number of range and range-rate cells would have to be processed.

No specific attention is given to receiver problems in this analysis. Operation on a single transmit pulse, and the possibility of cueing in range by another radar combine to reduce the data collection requirements. One could assume that the target returns could be easily recorded in the interval between scans of the antenna.

Pulse Generator/Transmitter and Antenna Comments

Since this assessment may differ notably from others, further clarification is warranted. The radar performance assessment of other investigators will likely differ most significantly in the pulse peak power which is assumed. The 9.5 MW considered here is much lower than the oft quoted gigawatt pulsers. The pulse generation technology can achieve source impedances of 1 ohm or less, and the quoted power output is often defined as the power delivered to a matched load. The delivered peak power scales inversely with the load impedance ($P=V^2/Z$). Practical antennas with appreciable radiation efficiencies have input impedances significantly greater than 1 ohm, and the TEM horn feed antenna being considered was assumed have been designed to present a 42-ohm surge impedance to the pulse generator.

The feed antenna and its transmission line will be integrated so that the input impedance can be controlled. However there are engineering constraints which limit the ability to achieve an antenna with a very low input impedance that can efficiently radiate high power signals. A frequently used broadband structure is a parallel plate waveguide which flares out to form a TEM horn. The separation of plates in the waveguide must be sufficient to prevent arcing under the high voltage excitation. A 1-cm spacing between the plates is chosen in this analysis.

If the antenna input impedance could be set to 1 ohm to match to the pulse source impedance, discharging 20,000 volts would generate a 100-MW pulse (only 10,000 volts would appear across the load due to the source/load voltage division). To get a 1-ohm input impedance, the parallel plates must be 3.7 m wide (air dielectric assumed) [2,3]. A waveguide this wide would actually not present a 1-ohm surge impedance to a 2.9-ns pulse, as will now be discussed.

If the width of the waveguide is a half wavelength or greater, higher order propagation modes are supported. These modes will distort the pulse being propagated, as well as present a different impedance to the source. For the 3.7-m wide parallel plate air line, these modes appear above 40 MHz. The 2.9-ns pulse being considered has f_{MAX}= 500 MHz, so the plate width must be less than 30 cm, and a width of half of that (15 cm) would be prudent to reduce the evanescent modes that reach the antenna. A parallel plate waveguide with 15-cm-wide plates separated by 1 cm would have a nominal input impedance of 25 ohms.

The above modal analysis yields steady state characteristic impedances; the transient effects experienced by the pulse generator further restrict the guide dimensions. Some intuition can be gained by considering this problem in the time domain. For the 3.7-m-wide plate line, the short pulse energy would not encounter the edge of the guide for 6 ns (assuming a source point in the center of the guide) and any effect of the edges would not be communicated to the feed until 12 ns. Until this time, the transmission line looks like an infinite parallel plate transmission line, which has a characteristic impedance of 377 ohms. Consequently, calculations for delivered power should be based on $V^2/377$, for pulses of less than 12 ns duration.

To generate a clean pulse it is asserted that the desired load impedance should be experienced by the pulse source within 0.1 pulse widths. To make the transit time from the center of the guide to the edge and back less than 0.1 pulse widths for the 2.9-ns pulse yields a guide width of 9 cm with an input impedance of 42 ohms.

[Note: Another transmission line/antenna structure that is popular is a slot in a ground plane that flares out to form a radiating element. This has poorer high voltage handling capability than the parallel plate because the slot width needed to achieve a given characteristic impedance is much smaller than the corresponding separation of parallel plates. The breakdown threshold is further lowered by the small radius of curvature (sharp edges) of the ground plane forming the slot. This makes the parallel plate approach more attractive for high power operation.]

The Analysis

To analyze the broadband performance of a system it is convenient to use linear system theory concepts. Representing the radar problem as a system transfer function, the radar range equation can be written:

$$S_r(f) = \frac{S_t(f)\sqrt{G(f)}}{\sqrt{4\pi}\,R}\,\frac{\sqrt{\sigma(f)}}{\sqrt{4\pi}\,R}\sqrt{A_r(f)}\,\sqrt{L(f)} \tag{9}$$

Where $S_r(f)$ is the Fourier transform of the received time domain signal. Equation (9) captures the frequency dependence of the various terms.

We will assess the performance of the system in terms of the energy received from the target in comparison to thermal noise energy. The transmit signal, receive signal, and thermal noise energies are defined as follows:

$$E_t = \frac{1}{Z}\int v_t(t)^2\,dt = \frac{1}{Z}\int S_t(f)^2\,df \tag{10}$$

$$E_r = \frac{1}{Z}\int v_r(t)^2\,dt = \frac{1}{Z}\int S_r(f)^2\,df \tag{11}$$

$$E_{noise} = kTN \tag{12}$$

Later in the derivation we will make use of a simplification to the integral for the transmitted energy, E_t, in which the monocycle pulse spectrum S_t is approximated as a constant across the bandwidth of the system, resulting in:

$$E_t \approx \frac{1}{2} S_t^2 \, \Delta f \tag{13}$$

Substituting Equation (9) into Equation (11) yields:

$$E_r = \frac{1}{2} \int \frac{S_t(f)^2 \, G_t(f) \, A_r(f) \, \sigma(f)}{(4\pi)^2 \, R^4 \, L(f)} \, df \tag{14}$$

The values used in this analysis are:

E_t = 13.8 mJ = -18.6 dBJ
$G_t(f) = G_1$ (constant) = 30 dB
$A_r(f) = A_1 \, (f_1/f)^2$, where A_1 = 23 dBsm
$\sigma(f)$ = constant = -10 dBsm for notional cruise missile,
= 0 dBsm for notional fighter.
$L(f)$ = constant loss = 5 dB
f_1 = 190 MHz (low end of band).
f_2 = 500 MHz (high end of band).
kT = -204 dBJ
N = 5 dB (Noise Figure).

Performing the integration using the above frequency dependencies (approximating the input signal spectrum $S_t(f)$ as a constant in the interval between f_1 and f_2) yields:

$$E_r = \frac{1}{2} \; \frac{G_1 \, A_1 \, f_1^2 \, \sigma \, S_t^2 \, (f_2 - f_1)}{(4\pi)^2 \, R^4 \, L \, (f_1 f_2)} \tag{15}$$

Using the simplification from Equation (13),

$$E_r = \frac{G_1\ A_1\ \sigma\ E_t\ \ f_1}{(4\pi)^2\ R^4\ L\ \ f_2} \tag{16}$$

Which for the cruise missile target yields:

$$E_r = -6.8\ \text{dBJ-m}^4 - 40\log(R) \tag{17}$$

Using the criterion that a SNR greater than 20 dB is desired,

$$SNR_{min} = \frac{E_r}{E_n} = 20\ \text{dB} = 192.2\ \text{dB-m}^4 - 40\log(R_{max}) \tag{18}$$

Solving Equation (18) for R_{max} results in:

R_{max} = 20.2 km for cruise missiles.
R_{max} = 35.9 km for fighters.

Ground Clutter

Clutter was not considered in the above analysis, though it would be a significant problem at the target ranges indicated. The current technology could conceivably support a simple two-pulse canceller (using a fiber optic delay line, for example) that could reduce the clutter enough for target identification.

The clutter cell area for the radar at a range of 20 km would be:

$$\begin{aligned} A_c &= R\ \Delta\theta\ \Delta r \\ &= 20{,}000\ \text{m} \cdot 52.6\ \text{mrad} \cdot 0.44\ \text{m} \\ &= 460\ \text{m}^2 \end{aligned} \tag{19}$$

The effective clutter cross section (assuming a constant clutter reflectivity of -30 dB) is:

$$\sigma_c = \sigma_o A_c = -3.3 \text{ dBsm} \tag{20}$$

For a clutter cancellation factor (from the two-pulse canceller) of 30 dB, the effective cross section of the clutter residue becomes -33 dBsm. This results in a 23 dB signal-to-clutter ratio on the -10 dBsm cruise missile. (Recall that a 20 dB signal-to-interference ratio was required for reliable identification performance.) If clutter motion degrades the obtainable cancellation, or the clutter reflectivity is higher than -30 dB, performance will decrease accordingly.

Conclusion

The modification of the VHF radar for UWB operation resulted in a cued system for target identification or target characterization which could operate out to 20 km on conventional cruise-missile-sized targets, and out to 36 km on conventional fighter-sized targets.

The limited capability predicted by the analysis is in part the result of the requirement to operate on a single pulse. Performance could be improved by the integration of multiple pulses but this would greatly increase the complexity of the receiver processing. An extension of the integration approach would be to use a coded pulse to get more average power, but the technology to generate high peak powers (>10 MW) at the high repetition rates needed (>10 MHz) does not exist[1].

Relaxing the UWB radar's requirement for single pulse identification (SNR = 20dB) to single pulse detection (SNR = 10dB) will increase the operating ranges by a factor of 1.8. The detection performance

[1] A hypothetical system that generates a burst of 1,000 10-MW pulses in 10 microseconds (a 100-MHz pulse rate) and compresses (integrates) these pulses on receipt would increase the available energy by a factor of 1,000, extending the usable radar range by a factor of 5.6 (resulting in R_{max}=114 km on the conventional cruise missile target.

of the UWB system is still significantly worse than that of the original VHF system. (The reason can be most directly seen by comparing the 13.8 mJ per pulse of the UWB system to the 5 to 10 J per pulse of the original system.) If such a UWB modification to a VHF radar were performed, it would probably find use only as a research tool, perhaps in the study of aircraft scattering characteristics.

REFERENCES

[1] E. A. Wolff, "Antenna Analysis," Artech House, Inc., Norwood, MA, 1988, p. 298.

[2] J. D. Kraus, "Antennas," Second Edition, McGraw-Hill, New York, NY, 1988, pp. 849-850.

[3] "ITT Reference Data for Radio Engineers," Howard W. Sams & Co., Inc., New York, NY, 1975, pp. 24-21 to 24-24.

APPENDIX C

PHENOMENOLOGICAL EFFECTS

APPENDIX C

PHENOMENOLOGICAL EFFECTS

[Contributed by Curt Davis[1]]

Molecular Relaxation and Signal Precursor Effects

Molecular relaxation and signal precursor effects are two phenomena which have been discussed in relation to the propagation of signals through attenuating media (such as microwave absorbers). The claim for relaxation is that a short pulse can propagate with reduced attenuation because molecules in the absorbing material do not have time to respond to the incident field. To achieve this the pulse width needs to be shorter than the "relaxation" time of the absorbing material. A related phenomenon involves the transient components of an pulsed signal that propagate through a dispersive attenuating media faster than the main body of the pulse (hence they are precursors to the steady state signal).

Both relaxation and signal precursors ultimately represent out-of-band effects, where the signal frequency components that penetrate the absorber are those that are outside of the material's absorption band.

Though the popular description of relaxation given above would lead one to think that it is the high frequency content of the pulse that is important, observed relaxation phenomena have involved the low frequency content. The resulting signal propagation properties are due to the low frequency μ (in ferrites, for example) or the reduced attenuation at lower frequencies (in liquid water). A typical equation describing the relaxation effect is given here (the Debye model):

$$n^2(\omega) = n_\infty + \frac{n_s - n_\infty}{1 + i\omega\tau} \tag{1}$$

where n_s and n_∞ are the low and high frequency limits of the refractive index, and τ is the relaxation time. Since elements of the equation are complex, the

[1]MIT/Lincoln Laboratory

expression represents the loss properties of the medium as well as the propagation velocity. In dielectrics, it is usually the variation of loss (attenuation) that is manifest in the relaxation effect. For water, in the frequency band of interest, the attenuation decreases steadily with decreasing frequency. The lower-frequency spectral components of a short pulse propagate with less attenuation, and the resulting pulse shape arriving at an observation point may not resemble the incident pulse, having been "filtered" by the medium.

The precursor effect can be thought of as a subset of relaxation phenomena, occurring when the material has a molecular resonance which creates an absorption frequency band. However, precursor effects can be contrived in any material that exhibits a relatively abrupt decrease or increase in refractive index as a function of frequency.

The precursor problem was first investigated by Sommerfeld and Brillouin [1,2]. They used a mathematical model for the frequency-dependent material dielectric constant surrounding a molecular resonance (the Lorentz model) which is still considered accurate.

$$n^2(\omega) = 1 + \frac{\omega_P{}^2}{\omega_0{}^2 - \omega^2 - i\omega\gamma} \qquad (2)$$

ω_0, ω_P, and γ are material parameters that determine the spectral location, amount of absorption, and spectral width of the resonance, respectively. (Equations 1 and 2 may each apply to the same material in different frequency regions.) A graph of this function is illustrated in Figure C-1. The material can be characterized as follows:

- At frequencies below resonance, the material has a given refractive index, n_2 (and its corresponding propagation velocity), which defines its "low frequency" characteristics.
- At frequencies in the vicinity of resonance, the material exhibits a high attenuation and a high index of refraction, n_{res} (leading to a slower propagation velocity). This is the absorption band of the material.
- At frequencies above resonance, a new plateau is reached at a lower refractive index, n_0 (with a faster propagation velocity), which defines the material's "high frequency" characteristics.

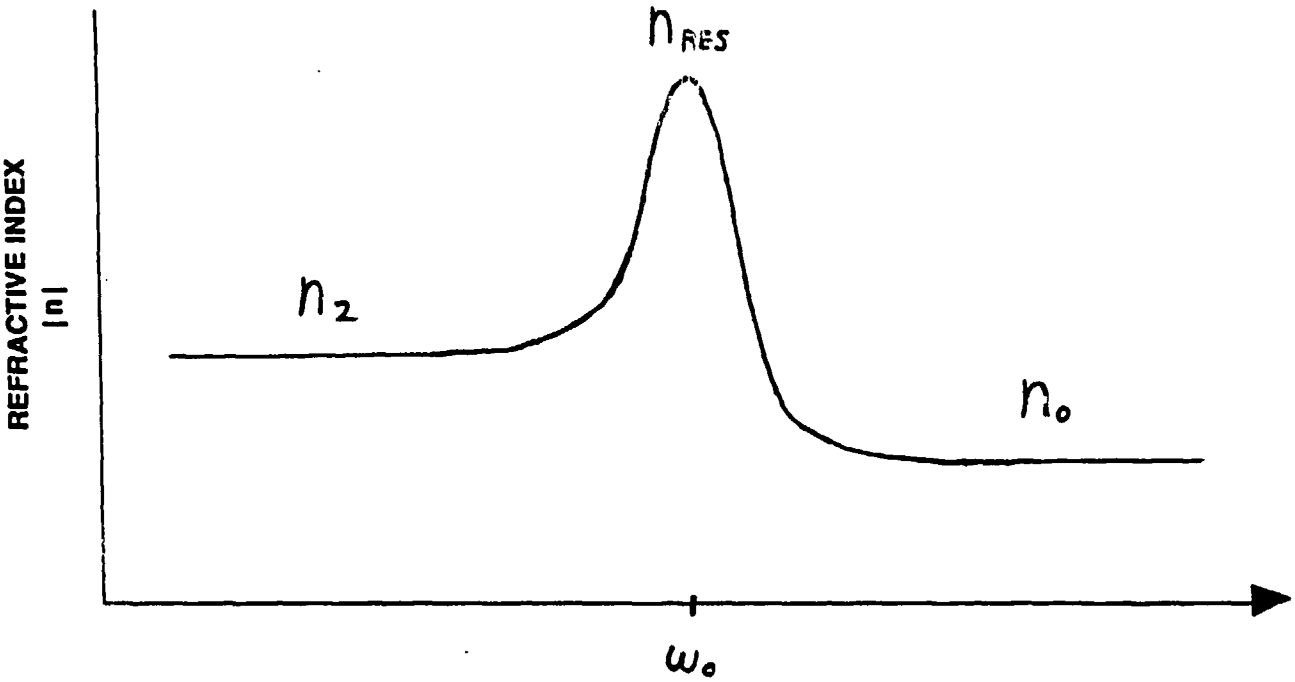


FIGURE C-1. REFRACTIVE INDEX SURROUNDING MOLECULAR RESONANCE

Typical materials have a number of resonances. As frequency increases past each resonance, the refractive index decreases to a new plateau, until ultimately a unity refractive index is reached (yielding signal propagation at the speed of light in a vacuum).

An example is now given for a hypothetical material with a single resonance, where the refractive index transitions from n_2 to n_0. The precursor effect can be most easily understood by considering a modulated pulse with a carrier frequency coincident with the material peak absorption. The material would be expected to effectively attenuate the signal in this case. This situation is illustrated in Figure C-2 for a narrowband pulse, where the entire pulse spectrum falls within the material absorption band. The pulse transmitted through the medium is delayed and attenuated.

If the signal pulse is short enough, the signal spectrum will spread above and below the absorption region, as illustrated in Figure C-3. With the signal carrier attenuated, the signal transmitted through the medium is dominated by those signal components that are outside of the absorption band.

Because of the high index of refraction in the resonance region, the outlying signal spectral components will reach an observer sooner than the components within the absorption band. In the original work in this area (where $n_0=1$), the transient signal arising from components of the pulse spectrum above resonance were called the Sommerfeld precursor, which propagates at the speed of light and arrives first in Figure C-3. The transient signal from frequency components below resonance were called the Brillouin precursor, which arrives later than the Sommerfeld precursor ($n_2>n_0$). The attenuated remnants of the main body of the pulse arrive last. In experimental verifications of this phenomenon, the signals employed have had more energy in the lower part of the spectrum so the Brillouin precursor has dominated; the Sommerfeld precursor is vanishingly small.

Both the relaxation and precursor phenomena are linear effects (superposition applies), and therefore readily treated with existing analysis techniques. The mathematical evaluation of the integrals involved in deriving the time domain response is daunting, and many papers have been written concerning solution techniques and approximations [3-5]. However, useful engineering results can be easily obtained by Fourier analysis using systems theory concepts. (Using Equation (2), the complex propagation factor as a

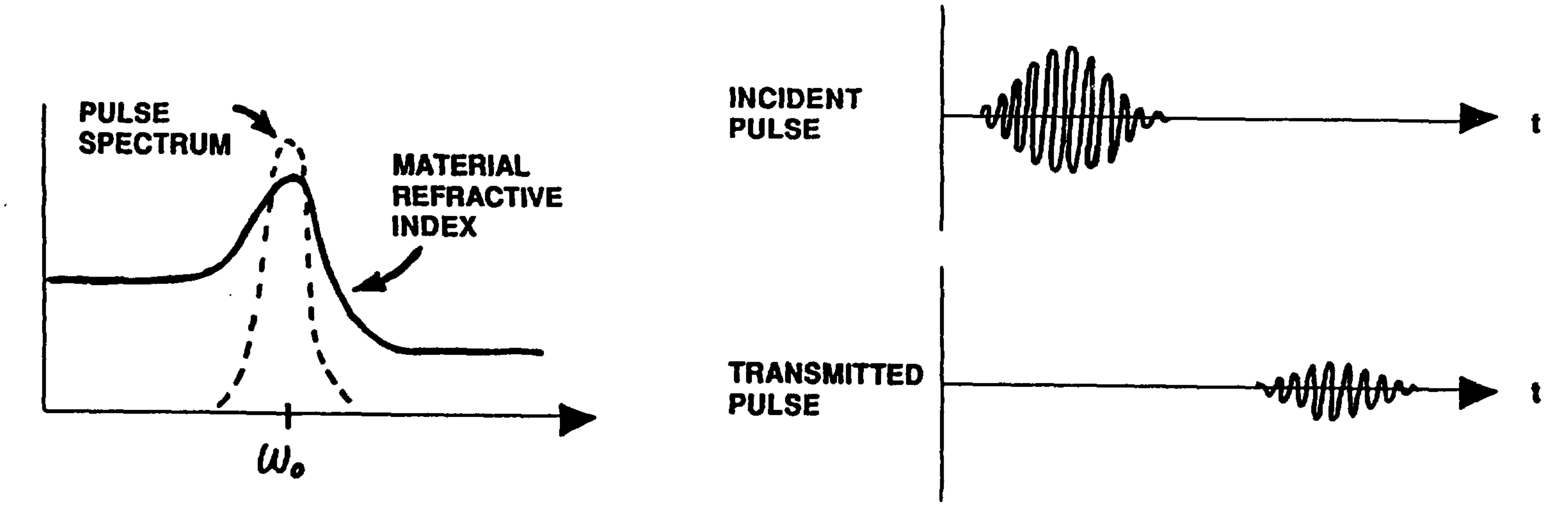


FIGURE C-2. MATERIAL RESPONSE TO A NARROWBAND PULSE CENTERED AT THE MATERIAL RESONANT FREQUENCY

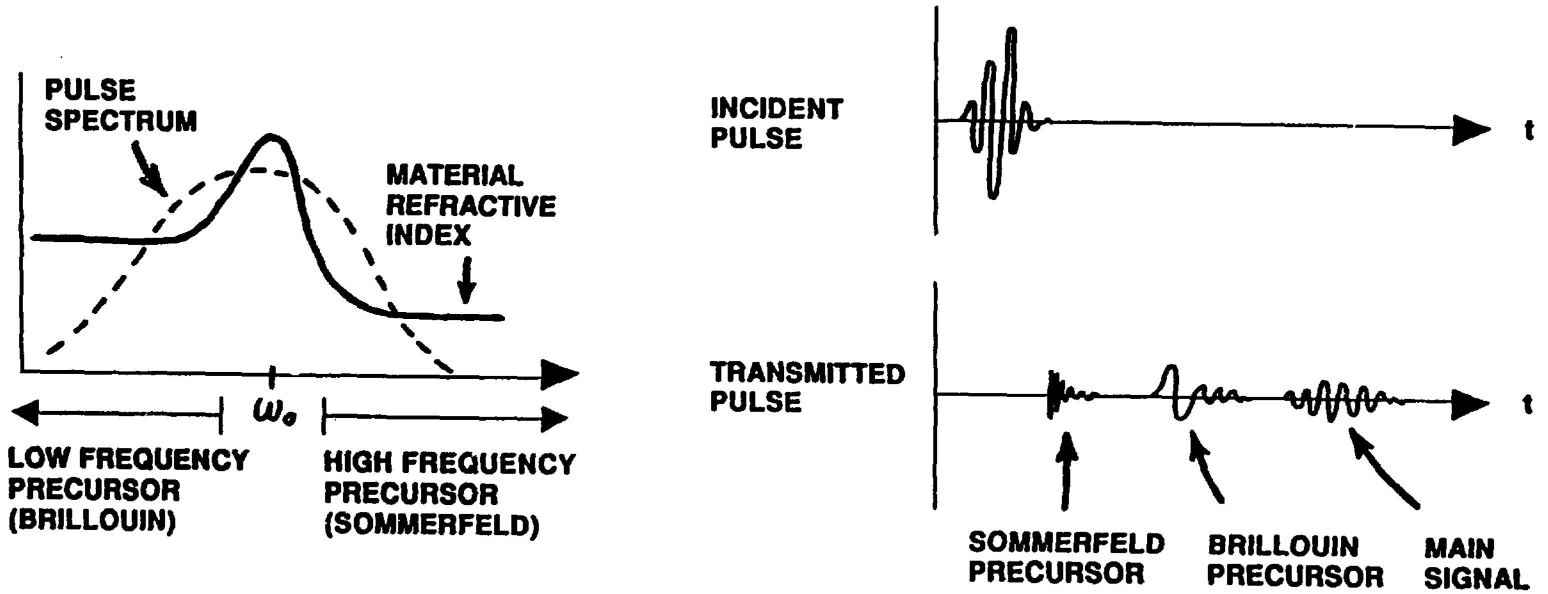


FIGURE C-3. MATERIAL RESPONSE TO A WIDEBAND PULSE CENTERED AT THE MATERIAL RESONANCE FREQUENCY function of frequency is derived. These values are then multiplied by the Fourier coefficients of the pulse spectrum and inverse transformed to the time domain to yield the transient response.)

It has been asserted that the precursor phenomenon is due solely to the shape of the time domain signal envelope. This is true in the sense that this envelope determines the signal's spectral extent (bandwidth) and, consequently, how much signal energy appears above and below the absorption band. The phenomenon exists whether a short pulse excitation is used, or a swept frequency measurement is made and transformed to the time domain (analogous to the analysis approach described above).

Though the precursor effect is an interesting phenomenon, it is difficult to imagine a practical radar application for it. In many common materials, the molecular resonances occur at optical frequencies, so are of no interest to radar engineers. Important resonance absorptions for radar atmospheric propagation occur for water vapor at 22 GHz and for oxygen at 60 GHz. These each have very broad absorption bands (>10GHz) and implementation of a signal bandwidth which spans the absorption band is clearly impractical.

More to the point, the energy which "penetrates" the absorbing medium in the precursor signal is due to spectral components outside of the absorption bandwidth. The energy in the band is heavily absorbed. It would be more efficient to just move the signal carrier frequency out of the material's absorption band. (A narrowband signal positioned above or below the absorptive resonance would achieve more penetration and less distortion.)

The same conclusion is reached for the more general relaxation effects. If there is a portion of a signal's spectrum which avoids absorption, it is most prudent to design a waveform to concentrate its energy in that spectral region.

REFERENCES

[1] A. Sommerfeld, "Über die Fortpflanzung des Lichtes in Dispergierenden Medien," *Ann. Physik*, vol. 44, pp. 177-202, 1914.

[2] L. Brillouin, "Über die Fortpflanzung des Lichtes in Dispergierenden Medien," *Ann. Physik*, vol. 44, p. 203, 1914.

[3] J. D. Jackson, *Classical Electrodynamics*, 2nd Ed., New York: Wiley, 1975, pp. 313-326.

[4] G. C. Sherman, K. E. Oughston, "Description of Pulse Dynamics in Lorentz Media in Terms of the Energy Velocity and Attenuation of Time-Harmonic Waves," Phys. Rev. Letters, vol. 47, no. 20, Nov. 16, 1981.

[5] C. D. Hechtman, C-W Hsue, "Time-Domain Scattering Parameters for a Lossy Dielectric," J. Appl. Phys., vol. 67, no. 5, Mar. 1, 1990.

APPENDIX D

CRISP, THE ZERO-AREA THEOREM, AND SUB-EXPONENTIAL ATTENUATION

APPENDIX D

CRISP, THE ZERO-AREA THEOREM, AND SUB-EXPONENTIAL ATTENUATION

[Contributed by George T. Ruck[1]]

During presentations by Dr. Barrett of Boeing and Professor Miller of the University of Rochester, and in the documents from Boeing, General Dynamics, and the University of Rochester, references have been made several times to work by M. D. Crisp who purportedly demonstrated the efficacy of so-called "Zero-Area pulses" in penetrating lossy media, and the observation of sub-exponential attenuation (SEA) by these Zero-Area pulses. The implication has been that a short "Zero-Area" pulse can somehow penetrate an absorbing medium without suffering the exponential attenuation usually associated with such media.

With a view toward assessing the validity of such claims a thorough study of Crisp's papers was made. It should be noted that Crisp, a physicist at Columbia University, was working with short coherent laser pulses at the time the papers of interest were published.

Crisp is an adherent of Fourier theory and, on page 1605 of Reference [1], he states explicitly, "<u>In terms of this spectral argument, the anomalously low absorption can be simply understood as the result of small absorption of those Fourier components which are far off resonance.</u>" Thus, in committee terms, <u>all</u> the phenomena Crisp describes are "out-of-band" effects for which Fourier analysis is valid. Crisp, in fact, uses Fourier transform theory for his analysis throughout his papers.

This fact appears to have escaped those who are using Crisp's concepts to claim that the phenomena is unique to fast rise time, short pulse waveforms and can only be understood on that basis. This is <u>not</u> correct, as indicated by Crisp himself in the above quote.

To actually understand what Crisp means by the "Zero-Area Theorem" and sub-exponential attenuation, we need to examine his papers in more detail. First, the absorbing medium model used by Crisp is a medium having a single

---

[1]Battelle

Lorentzian absorption line of spectral width $1/T_2$, where he defines T_2 as the transverse relaxation time of the medium.

The signal waveform used by Crisp is not a single-cycle or carrier-less (base band) pulse, but rather it is a coherent optical carrier which has been envelope modulated. Crisp used both a guassian and an exponential base band pulse to modulate the carrier and produce modulated envelopes such as are illustrated in Figure D-1. (That is, Figure D-1 shows an envelope detector display at various depths into the medium.)

Crisp essentially disregards the carrier in his analysis other than the critical fact that the signal carrier is centered exactly at the peak absorption frequency for the Lorentzian medium. (An analogous technique has been employed by EEs to calculate the response of notch filters to AM modulated RF waveforms in the generation of suppressed carrier DSB.)

After devoting several pages to initial definitions and assumptions, Crisp arrives at an expression given by his Equation (21) [our Equation (4) below] on page 1606 of reference [1]. He then states that "The remainder of this paper will be devoted to the study of Equation (21) for various input pulses."

We will examine Crisp's Equation (21) shortly, but first we need to look at the form of his input signal. Crisp, in his Equation (5), defines his input signal in terms of a linearly polarized electric field given by

$$E(z,t) = \xi(z,t) \cos [\omega(t - nz/c) - \phi(z,t)], \tag{1}$$

where ω is the optical carrier frequency, $\xi(z,t)$ is the pulse envelope modulation, $\phi(z,t)$ is a phase function, n is the dielectric constant of the medium assumed constant in both frequency and time, c is the speed of light, and z is the distance into the medium.

Crisp then defines the complex pulse envelope as

$$\xi(z,t)\ e^{i\phi(z,t)} \tag{2}$$

and works just with this quantity.

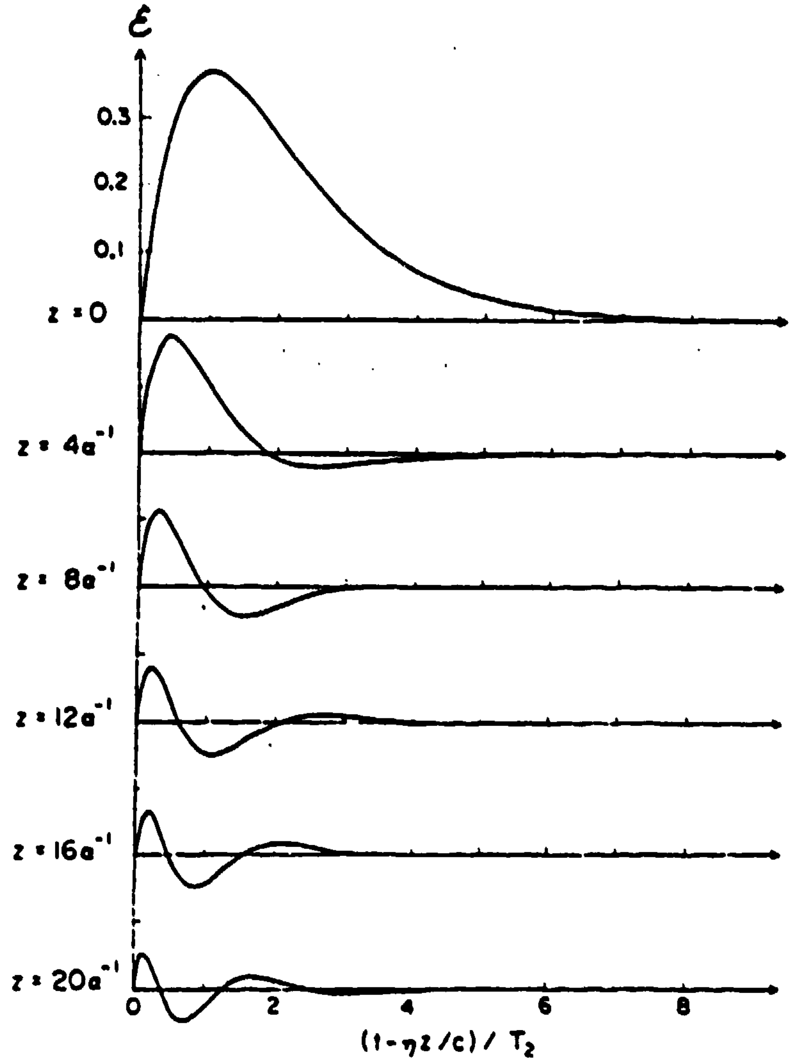


FIGURE D-1. PROPAGATION OF THE PULSE MODULATION WHICH IS INITIALLY DESCRIBED AS ξ_0 (t/τ) $e^{-t/\tau}$ U(t). Time is measured in units of T_2, and distance z is measured in Beer's Law absorption lengths α^{-1} (Néper distances). The different graphs correspond to different depths in the resonant medium. (From Reference [1])

The medium's effect on the pulse envelope is given by Crisp's Equation (20) in the form of

$$A(\nu) = \exp\left[- \frac{i\alpha_0 z}{i/T_2 + \nu} \right] , \tag{3}$$

which is actually the complex transfer function for the medium.

With these definitions in hand, we can now examine Crisp's Equation (21) from which all his results are derived. Crisp writes his Equation (21) as

$$\mathcal{E}(z,t)\, e^{i\phi(z,t)} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \epsilon(o,\nu) \exp\left(-i\nu(t-nz/c) - \frac{i\alpha_0 z}{i/T_2 + \nu}\right) d\nu \tag{4}$$

This equation is simply an inverse Fourier transform with a time translation given by nz/c, so that the time reference at any point z in medium is translated by a value corresponding to the time required to propagate to that point at the speed of light in the medium.

We observe that this is the inverse transform of the product of two frequency domain quantities. One of these, $\epsilon(o,\nu)$, is the spectrum of the pulse envelope at z=0, the other, the quantity

$$\exp\left[- \frac{i\alpha_0 z}{i/T_2 + \nu} \right] , \tag{5}$$

represents the effects of the medium. Thus, as it should, linear system theory is valid and the output pulse response is simply the inverse Fourier transform of the product of the input pulse spectrum and the medium transfer function.

Examining the medium transfer function for the pulse envelope, we see that the greatest attenuation occurs at $\nu=0$ (i.e., the DC component of the pulse envelope), where the attenuation is $e^{-\alpha_0 z T_2}$. At $\nu = 1/T_2$, or the edge of the absorption band, the attenuation is less or $e^{-\alpha_0 z T_2/2}$. As $\nu\to\infty$, the attenuation decreases to zero. Thus, to the pulse envelope, the "tuned notch filter" absorbing medium behaves as a high-pass filter.

This has considerable implication with respect to Crisp's so-called "Zero-Area Theorem" in which he indicates in his Equation (23) that the pulse envelope area (i.e., the integral of the area under the pulse shown in Figure D-1) decays with distance as $e^{-\alpha_0 z T_2}$. This is just the rate of attenuation of the DC component of the pulse envelope spectrum, as we indicated in the previous paragraph.

Thus, under the assumption used by Crisp, the pulse area (i.e., the DC component of the envelop) decays quickly in the medium leaving only a Zero-Area pulse. What is, in fact, really happening here can be made quite clear by examining the actual frequency domain behavior of both the signal and the medium.

Given a Lorentzian medium with a single absorption line centered at ω_0, the signal carrier frequency, with a bandwidth given by $\Delta\omega=1/T_2$, the transfer function in the frequency domain at any point z will be as illustrated in Figure D-2.

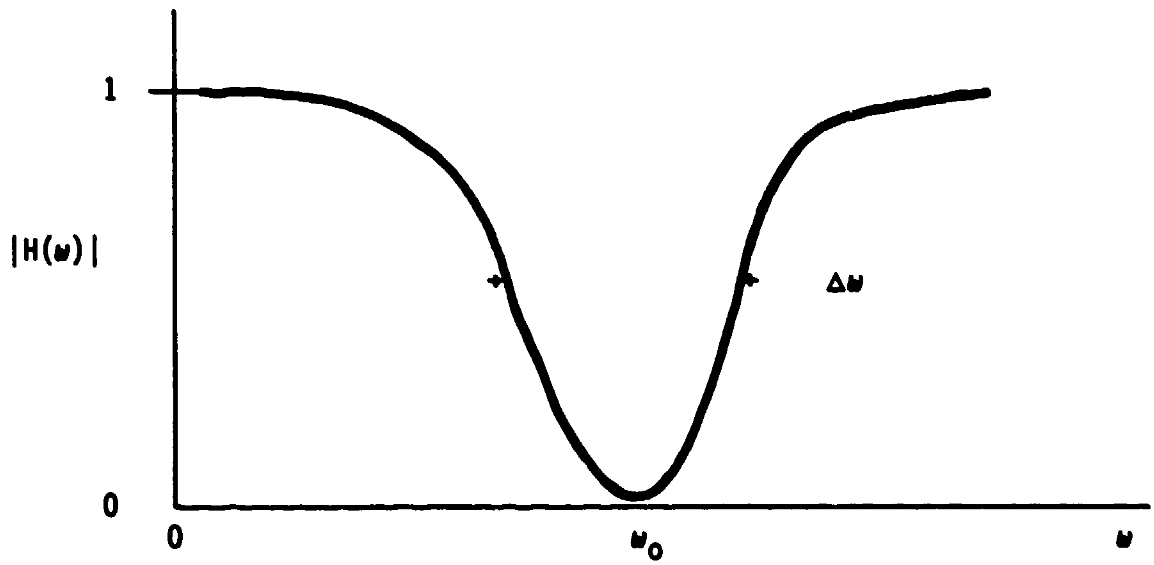


FIGURE D-2. TRANSFER FUNCTION FOR LORENTZIAN MEDIUM

Two cases need to be considered. One is when the pulse envelope spectrum is much less than $\Delta\omega$. In this case, the pulse spectrum as shown in

Figure D-3, lies entirely within the absorption band. The pulse signal in the time domain for this case will appear to propagate with little change in pulse shape and to attenuate exponentially.

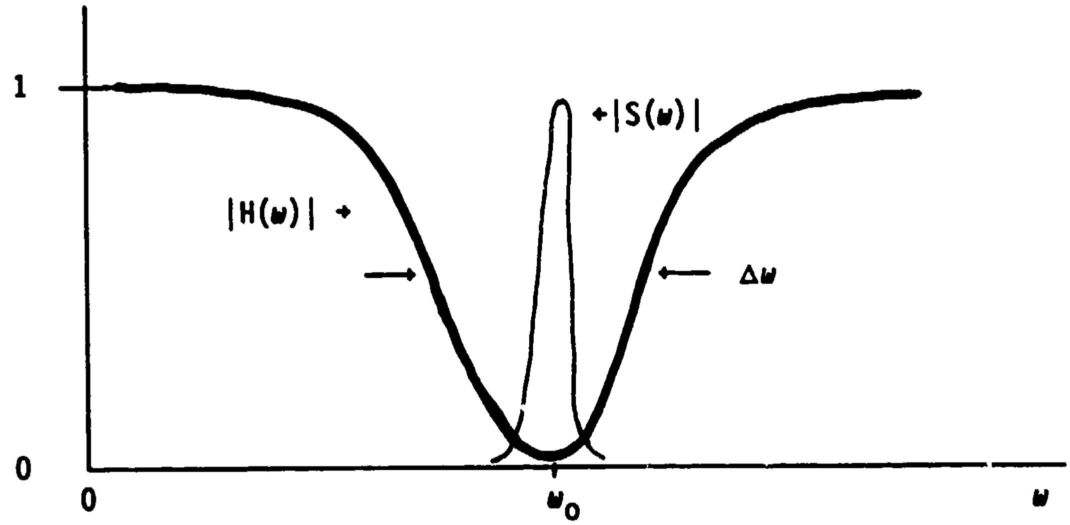


FIGURE D-3. PULSE SPECTRUM, CASE 1

In the second case, as illustrated in Figure D-4, the pulse is shorter than T_2 and has a spectrum with a width $1/\tau$, much wider than $1/T_2$.

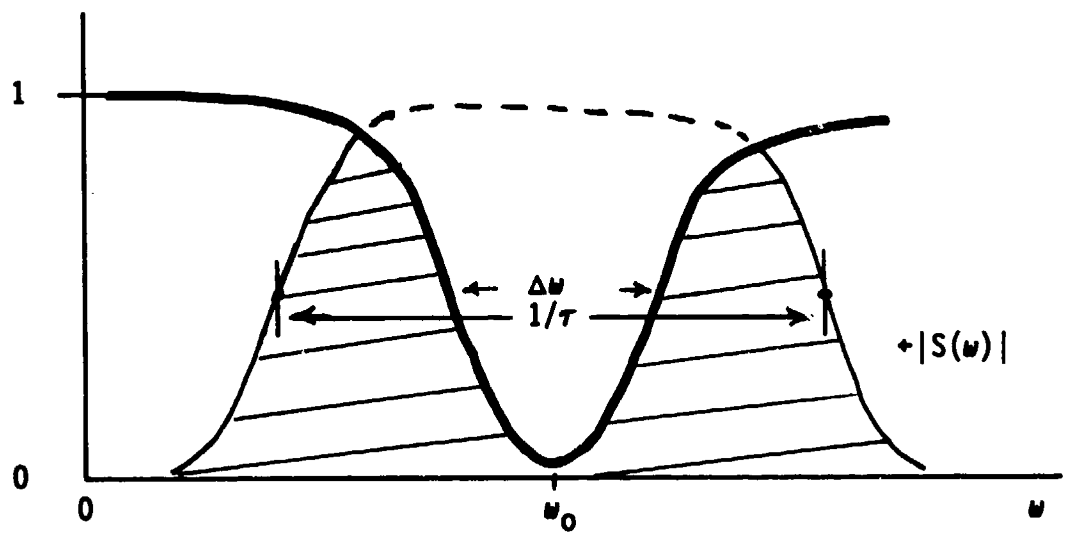


FIGURE D-4. PULSE SPECTRUM, CASE 2

For this case, as the pulse propagates the absorbing medium chews a hole in the pulse spectrum and eventually bifurcates into two remaining spectral regions associated with the out-of-band portions of the initial pulse spectrum.

Thus, Crisp's area theorem rather than being a fundamental tenet of pulse propagation appears to result from specific assumptions about the media properties, i.e., the DC component of the pulse envelope is attenuated most severely in his media (a high pass filter, if you will). [In the RF picture, the effective notch filter has attenuated the carrier component, leaving only the side bands.]

The sub-exponential attenuation (SEA) observed is, by Crisp's own statement, simply an out-of-band phenomena which is what one would, in fact, expect to observe. <u>Each Fourier component of the pulse is always attenuated exponentially</u>, the exponent value at each frequency, of course, being dependent upon the media. For a pulse with a spectrum which is virtually all contained within a media absorption band, the pulse will attenuate essentially exponentially and the shape will not change significantly. For a pulse whose spectrum extends out beyond the absorption band, the out-of-band components will attenuate very slowly, thus the pulse shape will change with distance, and the time domain presentation of the attenuation will not necessarily <u>appear</u> to be exponential.

The so-called "Zero-Area Theorem" results from the fact that when one centers the pulse carrier at the absorption line center, and then examines the behavior of the pulse envelope with respect to a translated zero frequency (corresponding to the carrier frequency), the maximum absorption will always result at zero frequency relative to the pulse envelope. Thus with distance, the DC envelope component rapidly disappears leaving in effect an AC envelope or "Zero-Area" pulse. [Every TV engineer knows that SSB and DSB have very poor low frequency response - that's why video is transmitted as VSB. A TV signal has to convey the low frequency vertical synch pulses.]

If an essentially "Zero-Area" pulse is created initially, this means that one is simply re-shaping the pulse spectrum so as to move more energy symmetrically outside the absorption line. The presence of the absorption line inherently creates a bifurcated spectrum for the pulse-media product when the pulse spectrum exceeds the line width. This bifurcation and its degree-of-symmetry are what produces the "Zero-Area" effect.

If one is interested in minimum attenuation then, insofar as possible, you simply radiate a signal whose spectrum is centered away from the absorption peaks. This conclusion is common knowledge, and Radar engineers have been doing this for quite some time!

It should also be noted that if a carrier-less (base-band) pulse is radiated, then it is always inherently Zero-Area since a DC component cannot be radiated.

The bottom line on this is that all of Crisp's observed phenomena, the so-called "Zero-Area Theorem", "sub-exponential attenuation", etc., can be explained by conventional, classical, linear system theory. No pulse-unique phenomena are involved, no magic way of subverting the attenuation encountered in a lossy medium has been discovered, and it is evident that those persons promoting "Zero-Area" pulses as a panacea for "seeing through" lossy media do not understand Crisp's analysis.

REFERENCES

[1] Crisp, M.D., "Propagation of Small-Area Pulses of Coherent Light through a Resonant Medium", Physical Review-A, Vol. I., No. 6, June, 1970, pp. 1064-1611.

APPENDIX E

SELF INDUCED TRANSPARENCY AND NON-LINEAR MICROWAVE MATERIALS EFFECTS

APPENDIX E

SELF INDUCED TRANSPARENCY AND NON-LINEAR MICROWAVE MATERIALS EFFECTS

[Contributed by David Nelson[1], Curtis W. Davis,III[2], and George T. Ruck[3]]

Self Induced Transparency

Introduction

Self induced transparency (SIT) is a particular non-linear optical effect in which a pulse of coherent light, with an incident energy above a critical value for the given pulse duration and propagation medium, passes through an optically resonant medium as though it were transparent. Below this critical energy value, the pulse is highly attenuated. The effect implies that the transmission of coherent light pulses through dissipative media can be dramatically enhanced over that of propagating pulses of ordinary (incoherent) light of the same frequency. In contrast to the relaxation and precursor effects discussed in Appendix D, the SIT signal is precisely tuned to the medium's absorption line and is not an out-of-band phenomenon. The early descriptions of the phenomenon are fairly colorful:

> "*The self-induced transparency effects observed in the laboratory are quite dramatic. An optical pulse at low intensity* [the time-averaged value of the magnitude of the Poynting vector] *incident on a resonant absorber is normally absorbed according to Beer's law,*
>
> $$I(L) = I_0 e^{-\alpha L}$$
>
> *where I_0 is the incident intensity, α is the [power] absorption constant, and L is the length of the absorber. αL is typically >5 for a SIT experiment, so that low-intensity pulses are almost completely absorbed. Suddenly, as I_0 is increased, the pulse propagates through the absorber as if it were transparent . . .*" [1]

---

[1]Department of Physics, Harvard University.

[2]MIT/Lincoln Laboratory

[3]Battelle

Such a propagation mechanism would certainly be of great interest to radar and EW engineers if it could be manifested somewhere in either the millimeter wave region or perhaps in the absorption bands of radar absorbing material. It might also be of interest to RF communications. For example, one might envision the possibility that it could provide a communication path with extremely low side lobes, making it difficult to intercept.

In addition to the dramatic effect mentioned above, other spectacular effects are observed to occur in the SIT regime. The pulse slows down and its velocity may be as small as 10 to 10,000 times less than the speed of light in the host medium. Further, the pulse shape can be severely distorted, and it may even break up into a series of pulses.

Elementary Quantum Description

Self induced transparency is a genuinely non-linear phenomenon which can be observed in a few very carefully prepared laboratory systems.[1-4] In simplistic terms, the effect arises when coherent radiation, with an appropriate envelope function and with a carrier frequency located precisely at the absorption line center frequency, is incident on a medium consisting of an assemblage of identical non-interacting two-level quantum systems. The "two-state systems" are an idealization of the complex atomic, vibrational and rotational energy levels which characterize real physical materials.

Historically, the basic idea is to adjust the signal intensity and width of the modulation envelope to drive two-state systems, which are initially in the ground state, into their excited state and then precisely back down to the ground state again. Lamb, in his review of the subject, has observed that under the appropriate conditions, "The leading edge of the pulse is used to invert the population and the trailing edge returns the inverted population to its initial state by means of stimulated emission."[5] The situation is to occur in such a way that the energy given to the system is coherently reradiated back into the electromagnetic field as the system is driven back to the ground state. If the attempt is successful, the stimulated emission remains coherent with the excitation pulse and no energy is lost to the two-level system because its final and initial states are identical. The delicate conditions permit the medium to, in essence, become a unity gain amplifier instead of an attenuator. Since no energy is lost, the electromagnetic energy propagates through the medium with little or no attenuation.

Although energy is conserved, the pulse shape will generally distort (unless the envelope is chosen to be a special soliton-like hyperbolic secant form[2]). As mentioned above, propagation velocities are very slow, typically 1,000 times smaller than those expected in the linear regime.

Experimental Work

The materials involved in this phenomena, to date, have been those which can be prepared in the laboratory to closely represent an ideal two-level system. Such material consists of an ensemble of identical two-level atomic systems which are essentially uncoupled from the rest of the world, at least during the duration of the experiments.

An indication of the difficulty in finding *any* material which exhibits this effect can readily be found in the relatively few successful experiments to date. In spite of its age, the most comprehensive study is still probably that of Slusher and Gibbs.[1] *Near vacuum* conditions were required to observe self induced transparency mediated by the 5s ——> 5p transition in a dilute rubidium gas. The original experiment by McCall and Hahn excited Cr^{3+} ions in a chromium doped ruby-rod sample which had to be cooled to liquid helium temperatures (4.2 degrees above absolute zero). The effect gradually went away with increasing temperature, disappearing entirely above 40 K (-233 C), because of an unwanted additional transition out of the upper state mediated by thermal phonons in the Al_2O_3 matrix.

Analysis

In the late 1960s and early 1970s, a number of theoretical and numerical studies of the SIT phenomena were published.[1-3,5,6] Very little more has been published in this area in the last 15 years.

Much of the analysis in the theoretical literature revolves around the conditions required on the size and shape of the pulse envelope for the SIT phenomena to exist. Little analysis has been devoted to the actual conditions required of the media in terms of the atomic or molecular interactions, transition times, relaxation times, etc. The criterion, usually seen in the theoretical literature, for the SIT phenomena to exist, is that a so-called "2π" pulse be used for the modulation envelope. What is a "2π" pulse?

The conditions necessary for self induced transparency are very difficult to satisfy in practice. To see why, consider the scaler component of an incident field propagating in the z-direction:

$$E(z,t) = \xi(z,t)\, e^{i(kz-\omega t)} \quad , \tag{1}$$

where $\xi(z,t)$ is a slowly varying ($\partial\xi/\partial t \ll \omega\xi$, $\partial\xi/\partial z \ll k\xi$) envelope function[5]. Radar engineers will recognize Equation (1) as a "bandpass" signal. The modulation function $\xi(0,t)$ is commonly called the complex "envelope and phase" description of the disturbance [$\xi(0,t) = R(t)\, e^{j\Phi(t)}$], and it essentially represents the "lowpass equivalent signal". The carrier is represented by the time harmonic phaser $e^{-i\omega t}$.

One can invoke the quantum mechanical system description and characterize suitable pulse modulation envelopes for the appropriate carrier wave, which will activate the SIT phenomenon. (In the simplified analysis, Φ is initially set equal to zero, and ω is tuned to the center of the transition line, ω_0.)

Upon solving for the quantum-mechanical transition rate induced by this perturbation acting on a two-level system with energy spacing $\hbar\omega_0 \approx \hbar\omega$, one finds that the condition for the SIT phenomenon to occur amounts to a requirement on the "area" under the normalized modulation envelope function[2]:

$$(2p_j/\hbar) \int_{-\infty}^{\infty} dt\ \xi(z,t) = 2\pi n \quad . \tag{2}$$

Here, p_j is the electric dipole transition matrix element for the jth two-level system, $\hbar$ is Planck's constant divided by 2π, and n is a positive integer. The pulse must be sufficiently short to preclude decay from the excited state to states other than the ground state and yet of sufficient duration and intensity to produce at least 2π units of area in Equation (2). Such a pulse modulated wave will drive the system from its ground state to an excited state and back to the ground state again. These envelope functions are called "2π" pulses because their "area", as defined by Equation (2), is 2π. This relationship is called the "area theorem" by McCall and Hahn[3].

Area Theorem

To examine the historical source of this so-called area theorem and its manifestation in π-pulses, 2π-pulses, and so on, we need to briefly examine an analogous situation which historically occurs in nuclear magnetic resonance effects. Consider, initially, a simple two-level nuclear system capable of existing in only two states, i.e., having two spin states (1/2) hf and -(1/2) hf.

For an ensemble of such nuclei in the presence of a DC magnetic field, the net macroscopic magnetic moment associated with the system has an average value oriented along the DC field direction. The nuclei can be considered to be precessing about the external DC field at the Larmor frequency $(\gamma/2\pi)\ H_0$, where γ is the gyromagnetic ratio and H_0 the external DC magnetic field.

This is illustrated in Figure E-1. We see that the individual nuclear magnetic moments are precessing around H_0 with essentially random phases and are either oriented in the H_0 direction or in the $-H_0$ direction depending upon the spin state. If there were an equal number of nuclei in both spin states then the resultant macroscopic magnetic moment M_0 would be identically zero. Since the upper level is more densely populated, however, a macroscopic magnetic moment exists and is responsible for the nuclear magnetic susceptibility.

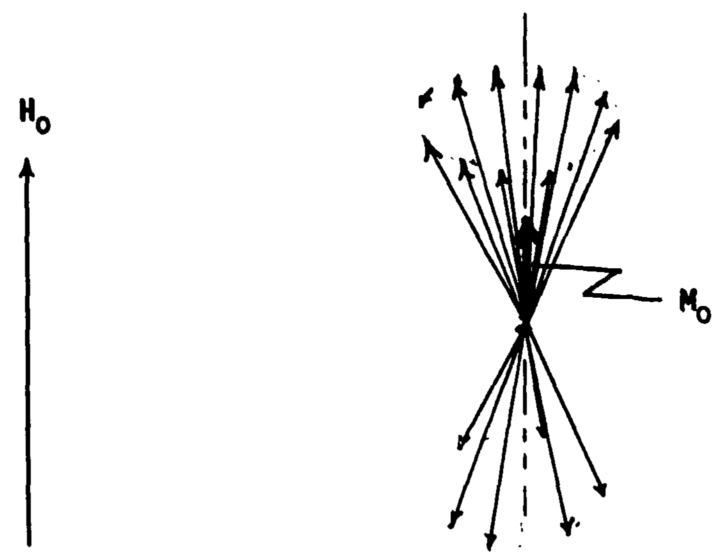


FIGURE E-1. MAGNETIC MOMENT FOR UNEXCITED TWO-STATE SYSTEM

The angle between the individual nuclear magnetic moment vectors and the external field H_o is usually called the "tipping" angle.

In the presence of a coherent RF magnetic field, H, whose carrier frequency equals the Larmor frequency, the randomly phased nuclear magnetic moments are forced into phase coherence by the RF field with a resulting macroscopic magnetic moment M which now precesses about H_o at the "tipping" angle θ. This is illustrated in Figure E-2.

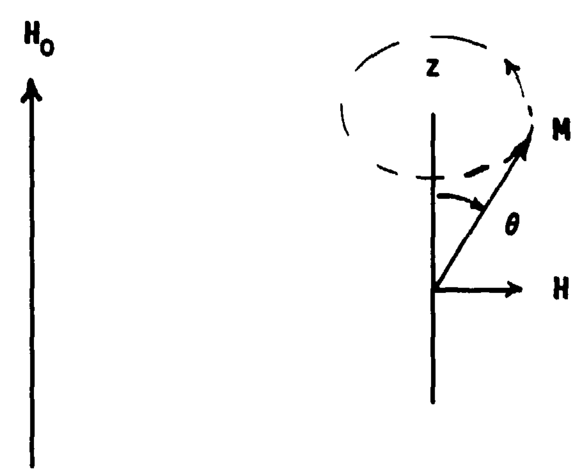


FIGURE E-2. EXCITED TWO-STATE SYSTEM

In terms of a reference coordinate system which is rotating at the Larmor frequency, the application of the RF field H at the Larmor frequency simply fixes the direction of H in the rotating coordinate system and rotates the macroscopic magnetization M away from the H_0 direction with an angular velocity γH.

If the RF field is applied over a time τ, then the magnetic moment M is rotated through an angle $\theta = \gamma H \tau$. Thus, the effective "tipping" angle value is given by $\gamma H \tau$ and can be rotated through values of $\pi/2$, π, 2π, and so on by the choice of the field level H and the application time τ.

Notice that if the tipping angle is π then the macroscopic magnetic moment M has been rotated so that it exactly opposes the initial magnetic moment M_0.

What has all the above to do with self induced transparency? The answer to this question was presented in a paper by Feynman in 1957.[7] Feynman and his co-authors demonstrated that *any* two-level quantum system can be analyzed in terms which have the same analytical form as the above. That is, the transition from state 1 to state 2 can be presented in terms of a transition of the above "tipping" angle over a value of π.

To quote directly from Feynman, the purpose of the paper was "To develop a simple but rigorous and complete geometrical picture of the Schrodinger equation describing the resonance behavior of a quantum system, when only a pair of energy levels is involved (the resulting picture has the same form as the well-known three-dimensional classical precession of a gyromagnet in a magnetic field)."[7]

Feynman further states, "Although this approach does not obtain results not accessible to straight-forward calculation, the simplicity of the pictorial representation enables one gain physical insight and to obtain results quickly which display the main features of interest."[7]

Thus, some of the features of SIT can be explained using the same formalism as nuclear magnetic-resonance, i.e., 2π pulses, and so forth. The fields involved are electric fields, however, and the transitions involve the electric dipole moments of the quantum system.

Discussion

McCall and Hahn, in their initial papers on self induced transparency, used the NMR formalism and demonstrated that, if some very restrictive conditions are met [(1) the inherent or homogeneously[1] broadened *absorption line width is zero* (a delta function type of absorption line), (2) the RF source carrier frequency is exactly matched to the absorption line frequency, and (3) a *perfect* two-level system is involved], then a 2π pulse area, dipole matrix product results in transmission through the media with zero loss.

Although conceptually useful in examining those pulse envelope conditions which can potentially result in SIT phenomena, this approach has some serious limitations.

One of these limitations is that the assumption of a delta function absorption line width implies infinite relaxation times. Thus, in the limit of very long pulse times a very low intensity field (approaching zero in the limit) would still result in self induced transparency. This is, of course, incorrect and the area theorem relationships do not provide guidance on the intensity threshold required for a medium to exhibit self induced transparency.

McCall and Hahn do impose the condition on the pulse width τ that $\tau \ll T_2'$ where T_2' is the relaxation (or dephasing) time for the medium. If this is used in Equation (2) as the upper limit for τ with a simple rectangular pulse, then, for the E-field, we obtain

$$E \gg \frac{h}{2pT_2'} \tag{3}$$

[1] The line-broadening mechanisms that operate by equally broadening the resonance profile of every individual atom in a collection result in **homogeneous broadening**. Mechanisms that operate by shifting the resonance profiles of individual atoms (thereby broadening the overall response of the collection, without broadening the individual responses) result in **inhomogeneous broadening**.

as a very general threshold condition on the field amplitude required to demonstrate SIT.

Equation (3) simply says that for a *perfect* two-level system for which a relaxation time T_2' is allowed, then a field intensity greater than

$$E \gg \frac{h}{2pT_2'}$$

is required to obtain self induced transparency.

Conclusions

We see from the above that the "area theorem" and the "2π" pulse envelope requirement came about because of the similarity in the algebraic form of a very simplified version of the coupled Schrodinger and Maxwell equations describing the SIT phenomena and the Bloch equations describing nuclear magnetic resonance. In fact, the same equations have been shown to describe *any* two-state system, including mechanical systems such as a rigid circular pendulum which has two states, either straight down, or the metastable excited state of straight up.

The key to the question of whether a microwave analog of the optical SIT phenomena exists is not associated with 2π pulses, per se, but rather with the details of the molecular interaction and relaxation processes operative at microwave frequencies.

One primary difference between the RF and optical phenomena is that, for the rotational transitions typically observed at microwave and millimeter frequencies, $kT \gg hf$ in contrast to optical frequencies where $kT \ll hf$. This means that the rotational levels are populated according to the Boltzmann distribution, and that in the microwave/ mm region the system interacts *strongly* with the ambient incoherent thermal radiation field.

In addition, for gases at ambient pressures, the collision frequencies are very high and the basic timing relationships *required* for SIT as suggested by McCall and Hahn do not appear to be applicable in the atmosphere for RF.

Further, even if all the above conditions were such that SIT could exist, the requirement on the coherent carrier frequency and pulse envelope times are such that it would not represent a wideband system in that *many* carrier cycles are required within a pulse envelope. The water vapor line at 22.237 GHz, for example, would require a pulse envelope on the order of 1 ns to meet McCall and Hahn's conditions, not a single-cycle or few-cycle 50 psec pulse. Such a signal would not satisfy the definition of ultra-wideband given in Section II of the main report.

The two-state quantum system described above was very idealized. The most severe limitation is that all dipole matrix elements p_j must be identical for the effect to work. Otherwise, what appears to be a "2π" pulse for one atom or molecule will in fact be far from this condition for most of the other atoms and molecules. Interactions of atoms and molecules with their environment and between internal degrees of freedom such as rotational and vibrational energy levels will inevitably produce a spread in the actual p_j's. This is almost always sufficient to nullify the effect. The required assemblage of identical two-level systems is very difficult to find in nature, which explains why experimental observations are confined to gases at low pressure or solids at very low temperatures. Saturation broadening and reduced absorption have been observed in microwave spectroscopy at cw power levels of the order of 10^{-4} watts/cm^2 for some gases at very low pressures. The physical basis for this is exactly the same as for self induced transparency (SIT). That is, the incident field produces a population inversion such that a higher energy level state has a greater population density than a lower energy level state. Such phenomena, however, have not been observed at atmospheric pressures in air at any intensity level all the way up to atmospheric breakdown.

SIT And Radar

Since each atom of material within the spatial extent of a pulse must receive one quantum of energy, the total input energy (and peak power) needed in the pulse can be determined. As described above, the materials in which SIT has been observed generally have been super-cooled or have had low densities (early demonstrations used liquid-helium-cooled ruby, or SF_6 gas at pressures of 5×10^{-5} atmospheres). Low densities or very low temperatures are required because thermal effects just discussed can overwhelm the critical electron population distributions necessary to support SIT.

The peak transmit powers required to support SIT in the larger material volumes associated with an air defense radar beam are substantial, and unlikely to be achieved at useful ranges in a practical system. In addition to the improbability that common materials will support SIT at RF, there is one other problem facing its application to radar for penetrating attenuating media (such as foliage or atmospheric absorption bands). Even if SIT were achieved on the radar-to-target path, target multiple scattering and dispersion will destroy the critical pulse shape (SIT is a non-linear effect, and superposition does not apply), and SIT will not be achieved on the target-to-radar path.

Comments

The Panel was presented no evidence that historical self induced transparency will occur in the more conventional materials relevant for radar applications. It was also suggested to the Panel that self induced transparency might provide a way to circumvent propagation attenuation for millimeter waves, and thus make possible the development of, for example, a 300-GHz radar. This also appears to be unlikely because the absorption of propagating radiation in the atmosphere is occurring in media which cannot be regarded as isolated two-level systems. The vibrational and rotational energies of the various atmospheric molecular constituents are strongly coupled at the temperatures of interest.

In the few systems where self induced transparency has actually been observed (e.g., rubidium gas), the phenomenon is well understood. It is also well understood why this effect does not occur outside of a few specialized materials under exceptional conditions.

As mentioned above, surprisingly little work has been performed on self induced transparency in the past 16 years. However, Professor Eberly (of the University of Rochester) informed a Sub-Panel that, due to the state of the art of instrumentation at that time, the historical experimental SIT work was confined entirely to long-pulse non-linear saturation effects (i.e., for pulse durations which extended over many, many carrier cycles). A distinction is to be made between short-pulse and long-pulse saturation, and there do exist computer simulations which indicate that short-pulse non-linear effects can be quite different from long-pulse effects. In the short-pulse case, the slowly varying simplifying approximations made on the modulation envelope function, $\xi(z,t)$, above are no longer valid, and recent analysis indicates that two physically distinct kinds of saturation occur.[8] With the current sources available, this phenomenological distinction may have experimental significance. The Panel thought it desirable for a brief review of the criteria necessary for self induced transparency in real materials to be performed by the JASONS summer study group (or some similar organization).

Low-Level Non-Linearities

In addition to SIT phenomena, it has been suggested that non-linear harmonic generation effects at microwave frequencies could be of potential use in target discrimination or detection. The exploitation of known non-linear effects (the saturation of ferrites, for example) requires peak power levels that are unlikely to be achieved at appreciable ranges in a practical radar system. The possibility has been suggested that previously undiscovered non-linear effects may exist which occur at much lower field intensities.

If such effects occurred in the manmade materials of a radar target but not in the natural materials of ground clutter, the radar receiver could be tuned to detect higher order harmonics generated by the non-linearity. There would be no clutter at these frequencies to compete with target detection, only thermal noise.

No such effect has yet been identified for materials of interest. Even if a non-linearity is discovered which can be induced at practical field strengths, the resulting effect may be many orders of magnitude weaker than the linear return. Previous attempts were made at the exploitation of target non-linearities (most notably metal reradiating radar, METRRA). Typical targets, obviously, *can* be made to radiate harmonics of the incident frequency if sufficient power densities are provided at the target. The problem, however, is that the radiated harmonic power density levels are *always* well below the scattered fundamental frequency power density and thus not particularly useful for detection. This is true even for an idealized harmonic generating target, that is one built out of diodes, for example. Any real target is, of course, much worse in this regard with harmonic conversion efficiencies typically in the -60 db or lower range.

From a discrimination standpoint, virtually *any* man-made object will produce a harmonic spectrum which can be highly variable, depending upon the specific state of the object. Thus, it is very *difficult* to utilize such radars for discrimination purposes.

Conclusion

The practicality of exploiting non-linearities will depend on the relative magnitudes of the effects. The numbers will determine whether better target detection can be achieved through these highly attenuated effects in a clutter free band, or through the use of the much larger linear in-band signal in the presence of clutter.

Summary On SIT And Non-Linear Effects

Summarizing, SIT phenomena have been observed at optical wavelengths in media which have been specially prepared to represent *ideal* two-level systems and *requiring* either liquid helium temperatures, 4.2 K, or essentially vacuum conditions. Such conditions clearly do not exist for *normal* microwave materials or at *ambient* atmospheric conditions. In addition, most microwave materials at ambient temperatures exhibit essentially a continuous absorption spectrum comprised of a number of independent, nearly homogeneous contributors. The oscillator lifetimes in these materials can range from subnanoseconds to tens of seconds. In general, one *can not* simply extrapolate short pulse effects observed in the optical region to the microwave region.

It is considered very unlikely that radiated short pulse signals in the microwave/millimeter wave region could induce SIT effects in the ambient atmosphere at any power density levels below those resulting in atmospheric breakdown.

The use of non-linear harmonic generation by potential targets is *not* a new concept, and the use of ultra-wide band sources in this context <u>does not</u> overcome the deficiencies inherent to this concept for *any* type of radiated waveform (i.e., cw, chirp, long pulse, ultra-wide band).

REFERENCES

[1] Slusher, R.E. and Gibbs, H.M., "Self-Induced Transparency in Atomic Rubidium", Phys. Rev., Vol. <u>A5</u>, pp. 1634-1659, (1972).

[2] McCall, S.L. and Hahn, E.L., "Self-Induced Transparency by Pulsed Coherent Light", Phys. Rev. Letter, Vol. <u>18</u>, pp. 908-911, (1967).

[3] McCall, S.L. and Hahn, E.L., "Self-Induced Transparency", Phys. Rev., Vol. <u>183</u>, pp. 457-485, (1969).

[4] Shen, Y.R., <u>The Principles of Nonlinear Optics</u>, Wiley, New York, (1984).

[5] Lamb, G.L., "Analytical Descriptions of Ultrashort Optical Pulse Propagation in a Resonant Medium", Rev. Mod. Phys., Vol. <u>43</u>, pp. 99-124, (1971).

[6] Slusher, R.E., "Self-Induced Transparency" in <u>Progress in Optics -- Vol. XII</u>, E. Wolf, editor, North-Holland, pp. 53-100, (1974).

[7] Feynman, R.P., Vernon, F.L., and Hellworth, R.W., "Geometrical Representation of the Schrodinger Equation for Solving Maser Problems", J. Appl. Phys., Vol. <u>28</u>, pp. 49-52, (1957).

[8] Eberly, J.E. and Milonni, P.W., <u>Lasers</u>, Wiley, 1988, pg. 218.

APPENDIX F

NATURAL RESONANCE THEORY

APPENDIX F

NATURAL RESONANCE THEORY

[Contributed by Ivan LaHaie[1]]

All natural resonance concepts are based on the singularity expansion method (SEM). The method relates the transient response (radar return) of a target to a set of poles in the complex frequency domain as follows.

Let g(t) represent the temporal impulse response of a target, that is, g(t) is an arbitrary component of the vector field scattered by a target under illumination by an impulsive plane wave incident field of arbitrary polarization and direction of incidence. The response can be decomposed into two components: a time-limited, "early-time" or forced response $g_f(t)$, due to the forced excitation of the target as the impulse sweeps over it at the speed of light, and a "late-time" or natural response $g_n(t)$, which is due to the residual "ringing" of the target after the impulse has passed by (much like the ringing of a bell after it has been struck). The natural response can be written as

$$g_n(t) = \sum_{m=1}^{\infty} a_m e^{-s_m t} \; ; \; t > t_L \quad , \tag{1}$$

where the a_m are independent of time and t_L is the onset of the late-time response. The return from an arbitrary incident wave form u_i is

$$u(t) = u_i(t) * g(t) = u_f(t) + u_n(t) \quad . \tag{2}$$

The natural frequencies s_m correspond to poles in the complex frequency response G(s) of the target, which is obtained via a LaPlace transform on g(t). The s_m have been shown to be independent of the form,

[1]ERIM

direction of incidence, or polarization of the incident field. Conversely, they depend quite strongly on the shape and material composition of the scattering body. As such, they are characteristic of a particular target and are invariant to the geometry in which g(t) is measured. This invariant property of the natural frequencies is the principle upon which all proposed natural resonance radar techniques are founded.

APPENDIX G

INTERCEPT RECEIVER PERFORMANCE ANALYSIS AND MEASUREMENTS AGAINST IMPULSE RADAR

APPENDIX G

INTERCEPT RECEIVER PERFORMANCE ANALYSIS AND MEASUREMENTS AGAINST IMPULSE RADAR

[Contributed by Merrill Skolnik[1] and Eli Brookner[2]]

Detectability Predictions

The detectability of an impulse radar depends on the type of intercept receiver employed. Intercept receivers can be (1) a receiver identical to the radar receiver, (2) the IFM (instantaneous frequency measurement) receiver, (3) a scanning superhet, or (4) a channelized (superhet) receiver. There are other receivers that could be considered, such as the radiometer and the crystal video, but they do not provide the ability to recognize the signal or to determine its frequency, as do some other receivers. The radiometer is the most sensitive of receives for detecting an unknown signal, but it is difficult to know that the signal detected by the radiometer is that of an ultra-wideband impulse radar or a narrowband signal.

The calculations made here are only approximate. More precise calculations will depend on detailed knowledge of the intercept receiver detection mechanism, including the role of an operator if one is employed. Precise predictions are not warranted since the conclusions are not overly sensitive to detailed assumptions about receiver detectability.

Radar Receiver as an Intercept Receiver

It is certainly possible to assume that the intercept receiver could use a receiver identical to that of the impulse radar. With conventional radars, this is not always a possibility because the exact frequency of the radar might not be known beforehand. However, with impulse

[1]Naval Research Lab

[2]Raytheon

radar, the receiver occupies a large part of the microwave spectrum. Not being precisely matched to the spectrum of the transmitted impulse signal produces an uncertainty no worse than many of the other uncertain factors in analyzing interceptability. The calculation of intercept range is made by finding the range R_i at which the signal P_i received at the intercept receiver is the same as the signal P_r at the radar receiver for a given set of radar characteristics. The radar range is given by the familiar equation

$$P_r = \frac{P_t G\ A_e \sigma}{(4\pi)^2\ R_r{}^4} \tag{1}$$

where

P_t = radar transmitted power
G = radar antenna gain
A_e = radar antenna effective receiving aperture
σ = target cross section
R_r = radar range to the target.

The radar signal received at the input of the intercept receiver is

$$P_i = \frac{P_t G}{4\pi\ R_i{}^2}\ A_i \tag{2}$$

where A_i = intercept receiver antenna effective aperture. We assume that the receiver noise figure, the integration of received pulses, and the losses are the same for both the radar and the intercept receiver. Equating P_i in Equation (1) and P_r in Equation (2) gives

$$R_i{}^2 = \frac{4\pi R_r{}^4\ (A_i/A_e)}{\sigma} \tag{3}$$

The target cross section is taken to be 1 m^2, the radar range is assumed to be 100 km, the intercept receiver has an antenna aperture of 0.1 m^2, and the radar antenna aperture is taken to be 10 m^2. (This radar performance can be achieved, for example, with a conventional S-band radar with about 0.05 J per pulse, 10 pulses integrated, an antenna gain of 40 dB, a 3-dB noise figure, a required signal-to-noise ratio of 15 dB, and system losses of 10 dB.) Substituting into Equation (3), the intercept range is

$$R_i = (4\pi)^{1/2} \ (100{,}000)^2 \ (0.1/10)^{1/2} \ (I)^{1/2} \tag{4}$$
$$= 3.54 \times 10^9 \text{ m} = 1.91 \times 10^6 \text{ nmi} \quad .$$

This assumes that the main beam of the antenna is pointing in the direction of the intercept receiver. If the radar antenna has 40-dB sidelobes, the intercept receiver will detect the radar sidelobe radiation at a range of about 19,1000 nmi. If we assume that the intercept receiver bandwidth B_i is not matched to that of the impulse radar B_r, the range will be further reduced in proportion to $(B_i/B_r)^{1/2}$. If B_i = 10 MHz and B_r = 10 GHz (pulse width = 0.1 ns), the intercept range is reduced by 0.0316, which results in 604 nmi for detection with 40-dB sidelobes and 60,400 nmi for main-beam detection. Even accepting additional degradation in the intercept receiver sensibility to allow for inefficient signal integration or a poorer noise figure, the intercept range in the main beam will still be quite large, and the range in the sidelobes will be respectable.

Measured Performance

The Naval Research Lab (NRL) performed measurements of the detection capability of two intercept receivers when the input was that of an impulse radar.

A commercial IFM receiver (Argo AR-625) covering from 2 to 4 GHz with a sensitivity of -78 dBm with a pulse 100 ns or longer, was tested with a signal that approximated a single-cycle within its bandwidth. There are two parts to the IFM. One part is the crystal video receiver which provides detection. The other part is a delay line and mixer that provide the frequency measurement. The experimental impulse radar signal was readily detected by the crystal video portion of the IFM receiver. The short pulse is stretched, as might be expected. The sensitivity was measured as -57 dBm. However, no frequency measurement was possible because the delay line in the IFM was too long compared to the duration of the impulse radar waveform.

A measurement was also made with a prototype channelized receiver with frequency coverage from 7.87 to 9.15 GHz. The impulse radar waveform in this case was about six cycles in duration. The receiver consisted of 64 contiguous channels, each with 20-MHz bandwidth. The video response was 3 MHz. Receiver sensitivity was about -68 dBm. The channelized receiver is supposed to measure the signal's frequency and the pulse repetition rate. All bands responded simultaneously to the radar waveform. The measured peak sensitivity was about -21 dBm. However, no valid measurement could be made of the pulse repetition frequency over the values from 1 to 10,000 pps.

Thus, detection of the impulse radar signal was accomplished, but information extraction was not. The ability to obtain information as to the parameters of the signal in this demonstration is not considered a fundamental limitation. These receivers were designed to recognize signals quite different from those of an impulse radar. An intercept receiver optimized to detect an impulse radar signal should therefore be designed differently than a receiver that is supposed to detect conventional radar signals.

It has also been observed by NRL that the design of some spectrum analyzers is such that they cannot detect a single-cycle waveform. This is not to say that single-cycle waveforms cannot be detected by a spectrum analyzer--only that they are not detectable by some instruments. It might be noted that some intercept receivers cannot recognize the presence of certain pulse compression waveforms of relatively conventional design.

This is not to say that pulse compression radars are LPI, only that some receivers are not capable of recognizing them. These are not fundamental limitations, however. Receivers have been designed and built to see almost any type of radar waveform.

Impulse Radar and Antiradiation Missiles (ARM)

In order to launch an ARM, the launching platform must first recognize the radar signal it wants to attack and determine its direction. Thus, the discussion of the detectability of impulse radar signals above is applicable as well to ARM. The Panel concluded that a properly designed receiver can detect and recognize impulse radar signals well enough to launch an ARM. Once launched, the receiver in the ARM must continue to recognize its target signal and home in its direction. The ARM cannot have as sophisticated a receiver as can the platform that launches it.

In some respects, however, the ARM problem is made easier with an impulse radar; in other respects, the problem is more difficult. An impulse radar signal might be easier for the ARM to detect and home on because it is difficult to have low antenna sidelobes with an impulse radar. This is especially true when the radar employs a phased array antenna. The measurement of the angle of arrival of the impulse radar signal by conventional means will be difficult if a large portion of the radar signal spectrum is employed. However, an angle measurement can be made using only a narrow part of the available impulse radar spectrum. It is also possible, in principle, to determine the direction to the impulse radar by the shape of its received signal, since the waveform will be a function of the angle.

Thus, it is not certain whether the net result of an impulse radar on ARM is good or bad, but it does not seem that the impulse radar makes ARM guidance inoperable. As with many other things, the ARM needs to be tailored to the type of signal it will encounter.

Final Comments

Conventional LPI radars have not proven practical unless the performance of the radar is severely reduced, something that is unacceptable in a military radar. Impulse radar does not change this observation. Adversely affecting ARM guidance is slightly easier to do for the radar system designer than is achieving LPI, but any advantages offered by impulse radar do not seem to provide sufficient improvement to be a major reason for justifying its development. Claims that impulse radar is undetectable by an intercept receiver or that it has significant anti-ARM capability have not been substantiated. Instead, it has been shown that impulse radar signals can be detected, that it is not LPI, and that it cannot be relied upon as a defense against ARM.

APPENDIX H

IMPULSE RADAR ASSESSMENT FOR AIR DEFENSE SURVEILLANCE

IMPULSE RADAR ASSESSMENT FOR AIR DEFENSE SURVEILLANCE[1]

[Contributed by Nicholas M. Tomljanovich and Jr. David R. Kramer, Jr.[2], Curtis W. Davis III[3], and J. Leon Poirier[4]]

Abstract

Impulse or Ultra-Wideband (UWB) radar has received considerable interest recently as a system that might offer improved surveillance against low-observable targets. Many claims have been raised on the merits of impulse radar for Air Defense applications and several proposals have been made to the Air Force for funding the UWB technology. A Red Team comprised of Lincoln Laboratory, MITRE, and RADC personnel was formed to evaluate the utility of impulse radar for Air Defense.

This paper presents the results of a strawman airborne radar design study conducted by the Red Team to establish the key technical issues and arrive at overall conclusions. Time-domain target response calculations are used to size the radar system, followed by calculations of the clutter suppression requirements, signal processor considerations, and EMI concerns.

Introduction

A study was conducted to determine the major parameters of a strawman airborne impulse radar configured for the long-range surveillance of low-observable targets [1]. The impetus for this study is that conventional radar systems are being stressed by this difficult Air Defense problem and UWB radar has been proposed as a potential surveillance alternative.

---

[1]Submitted May 6, 1990, to Los Alamos Symposium on Ultra-Wideband Radar for inclusion in the Symposium Proceedings.

[2]MITRE

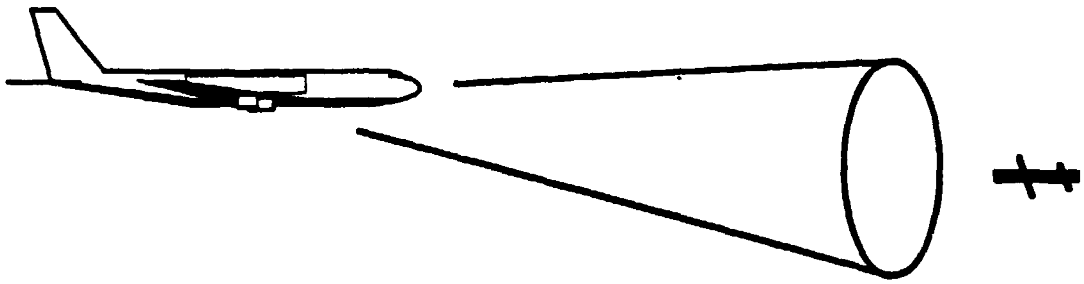
[3]MIT/Lincoln Laboratory

[4]Rome Air Development Center (RADC)

In evaluating the applicability of a new technology, it is always desirable to conduct a system design study to determine how the new approach satisfies all the requirements of a given application. One usually finds that the technological edge of the new approach entails certain other, often concealed, disadvantages. An engineering system trade-off is required to put the applicability of the new approach into proper context.

The major design parameters were based upon operational constraints and the projected level of technology. The antenna array size was limited by the airborne platform. A fuselage-mounted array array of 600 elements covering an area 20 m wide and 3 m high was assumed. Given the aperture size which is consistent with proposed advanced airborne radar systems, the number of elements and the array element spacing is based upon the length of the generated pulse. A nominal pulse length of 1 nsec was selected because of its general availability with existing pulse generators. For this array size and pulse length, the effective beam size is 1.3-degree azimuth and 8-degree elevation. The operational scenario of this radar will require that it scan 120 degrees in azimuth with a 20-sec revisit time, and the pulse repetition of 500 Hz was selected to provide a maximum number of pulses for signal integration without the inherent limitations of range ambiguities to the desired detection range of 200 nmi (Figure H-1).

The performance of a narrowband radar can be predicted using the radar equation. The basic radar equation expresses the received power in terms of the transmitter power, the gain of the transmitting antenna, the effective area of the receiving antenna, and the radar cross section (RCS) of the target. For a UWB radar, each of these terms are frequency-dependent. Therefore, an accurate representation for predicting the sensitivity of a UWB radar requires an evaluation of the frequency-dependent range equation. This is accomplished by expressing each frequency-dependent factor as a transfer function and then performing a Fourier transform of the product of these transfer functions over the spectrum of the UWB signal. The time-dependent voltage response at the receiving antenna is the correlation of the response of three linear filters: the signal spectrum [S(f)], the antenna transfer function [T(f)], and the scattering response from the target [$\sqrt{\sigma(f)}$]. Each of these functions is complex valued, having both an amplitude and phase. The



<u>Basic Parameters</u>

600 Elements, 20 m x 3 m Side Mounted Array

1.3° Az x 8° El Beam

120° Azimuth Scan Coverage

R_{max} = 200 nmi

PRF = 500 Hz

FIGURE H-1. STRAWMAN AIRBORNE SURVEILLANCE RADAR

radar cross sections of a nominal cruise missile and one shaped to reduce RCS are shown in Figure H-2. These were calculated using a Geometrical Theory of Diffraction (GTD) RCS prediction code. The generated pulse has a low pass characteristic since the high frequency content of its spectrum is limited by the rise time. From the antenna reciprocity principle, the transmitting transfer function is proportional to the receiving transfer function times frequency. Therefore, the combined response of the transmitting and receiving antennas has the character of a high pass filter, expressing the physical fact that DC cannot be radiated by an antenna. The scattering from a finite size target has a band pass characteristic with its maximum in the resonance band where the target size is approximately 0.5 wavelengths long. The overlap of these three filters determines the system sensitivity.

Strawman Impulse Radar Sizing

The transfer function approach described in the prior section is used to compute the spectrum of the return pulse received by the strawman impulse radar after being scattered from the shaped cruise-missile-type target. From the radar range equation, the normalized received power at frequency f, $P_n(f)$, is given by:

$$P_n(f) = \left(4\pi R^2\right)^2 \frac{P_{rec}(f)}{P_o} = \frac{4\pi f^2}{c^2} |A_e(f)|^2 \, S(f)^2 \, \sigma(f) \qquad (1)$$

where $P_{rec}(f)$ is the received power spectral density, P_o is the transmitted peak power, $A_e(f)$ is the effective antenna aperture for both transmission and reception, S(f) is the normalized transmitted signal spectrum, and $\sigma(f)$ is the target RCS. The waveform of the generated signal used to derive the normalized receiver power spectrum shown in Figure H-3 is a half-cosine wave pulse of one nanosecond duration. The antenna used for transmission and reception is a transverse electromagnetic (TEM) horn with a frequency-independent receiving transfer function for f $\geq$ 0.25 GHz and a horn aperture height of 12 cm. An array aperture excitation efficiency of 100 percent was

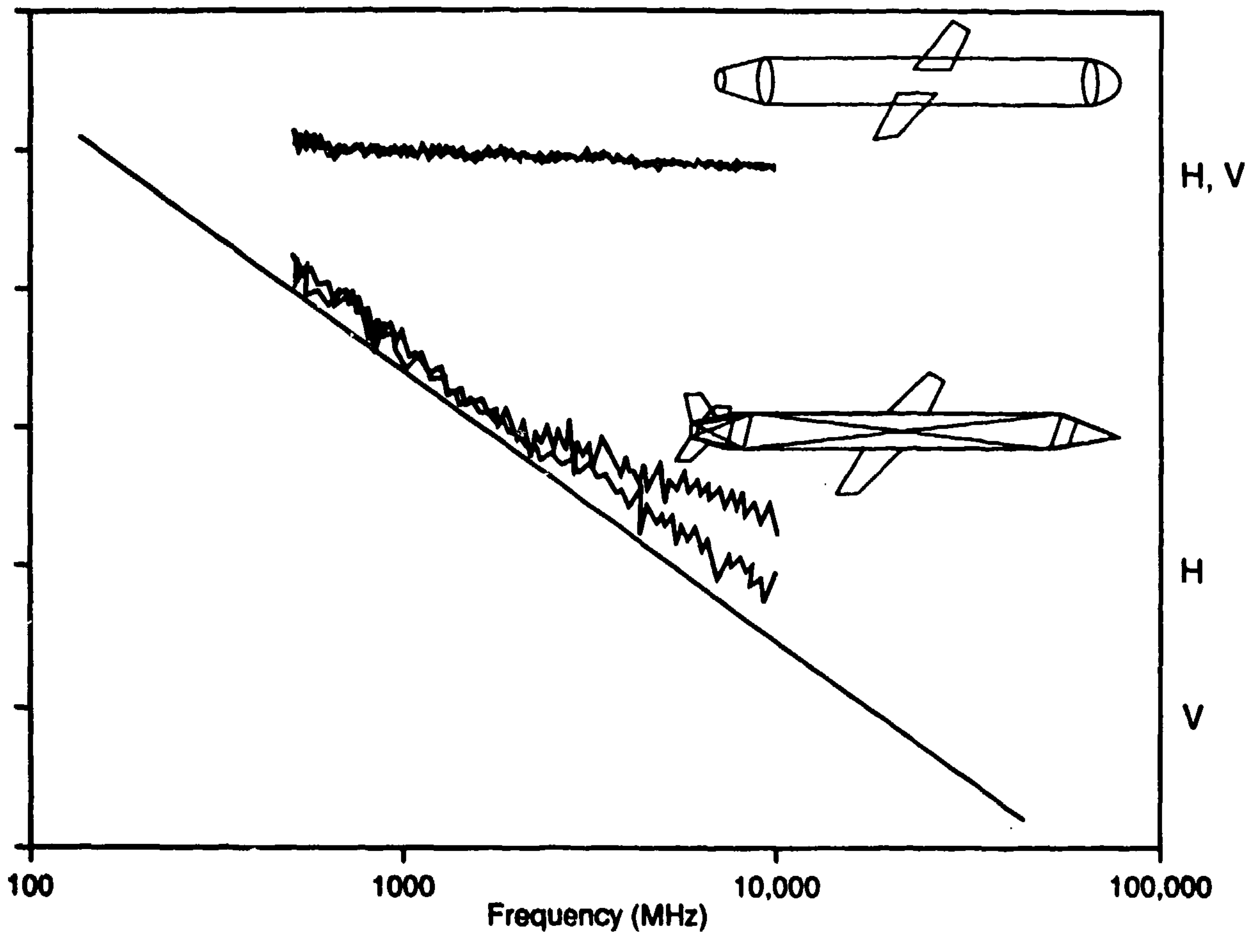


FIGURE H-2. FREQUENCY DEPENDENCE OF ASPECT ANGLE AVERAGED RCS FOR CRUISE MISSILE MODELS (θ,0-60)

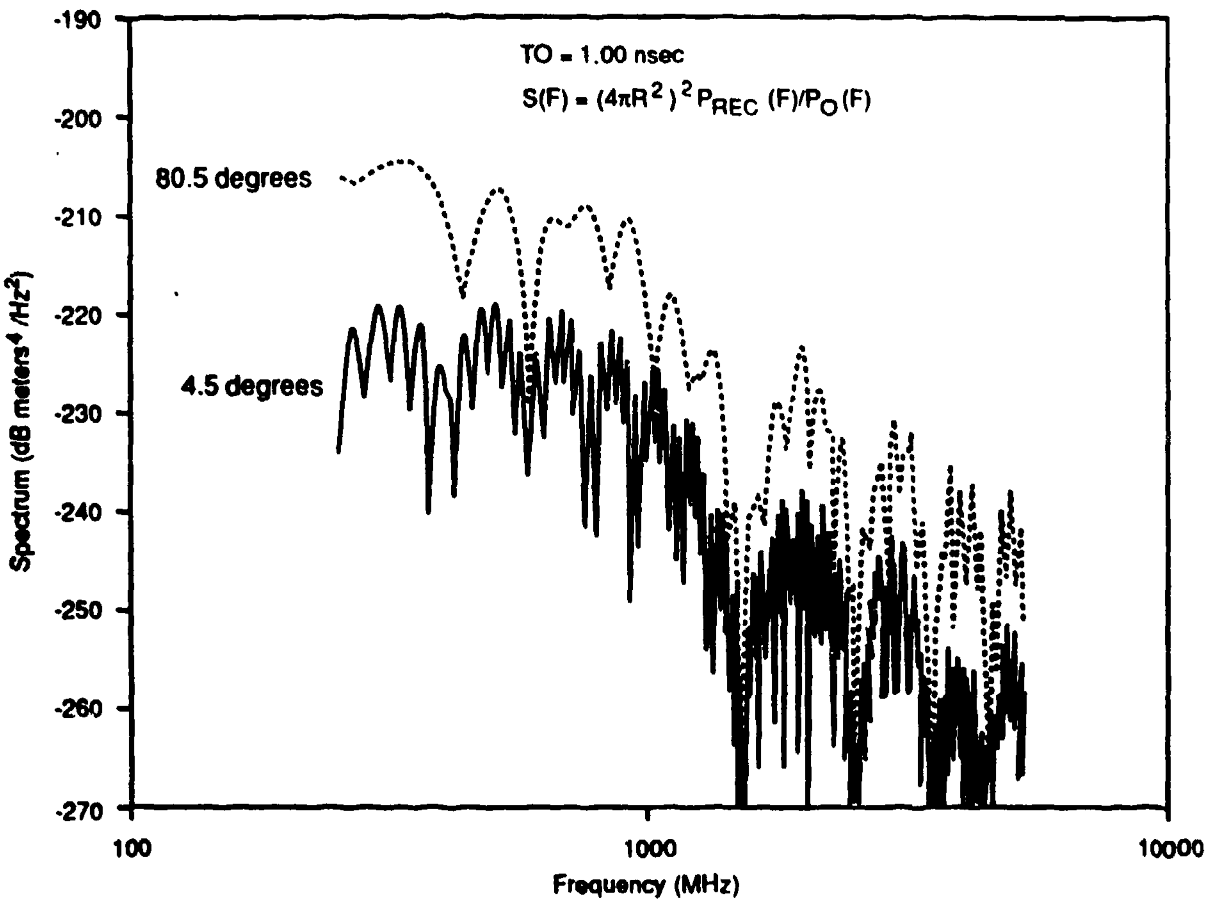


FIGURE H-3. SPECTRUM OF RETURNED PULSE FOR SHAPED CRUISE MISSILE (VERTICAL POLARIZATION) also assumed. Two cases were considered, one for the target approaching the radar at a near nose-on heading of 4.5 degrees and one for aheading of 80.5 degrees relative to the radar.

Figure H-4 shows the time response of the received pulse and was obtained by the Fourier transformation of the power spectrum presented in Figure H-3. The spectrum extends from 250 MHz to 5.25 GHz. In order to obtain the correct time domain response, it is necessary to compute the Fourier transform of the received voltage, which is proportional to the square root of the received power $\sqrt{P_n(f)}$. Note that the correct phase must be associated with each of the factors S(f), $\sigma(f)$, and $A_e(f)$. The lower curve, corresponding to the received signal for the near nose-on viewing (i.e., 4.5 degrees from nose-on), shows that there are three distinct returns, one from the nose tip, one from the edge between the nose cone and the fuselage, and one from the back edge of the fuselage. The first observation is that the response to an ultrawide waveform resolves the scattering centers of the target into individual pulse returns. An optimum matched filter receiver could maximize the peak signal by coherently combining the different peaks from the scattering centers. However, implementation of this type of receiver requires knowledge of the size, shape, and orientation of the cruise missile target. Using a suboptimum filter will incur mismatch losses that could be particularly severe for large targets comprised of many scattering centers. For the strawman sizing, a threshold detection was used that selects the strongest signal return. For the shaped cruise missile target, whose return is seen to be comprised of three scattering centers, the matched filter detector might increase the sensitivity by 2-3 dB. Figure H-5 presents estimates of the peak power requirement per element of an N-element array for detecting a shaped cruise-missile-type target. These estimates are based on achieving a single pulse signal-to-noise (S/N) ratio of 10 dB using the received power estimates for the strongest return from the near nose-on heading case of Figure H-4. The noise power is calculated to be -114 dBW for T = 300 degrees K and B = 1 GHz. The smaller number to the left of the curves represents the peak power requirement per element if a 20-dB coherent processing gain is achieved by integrating 100 pulses to perform detection.

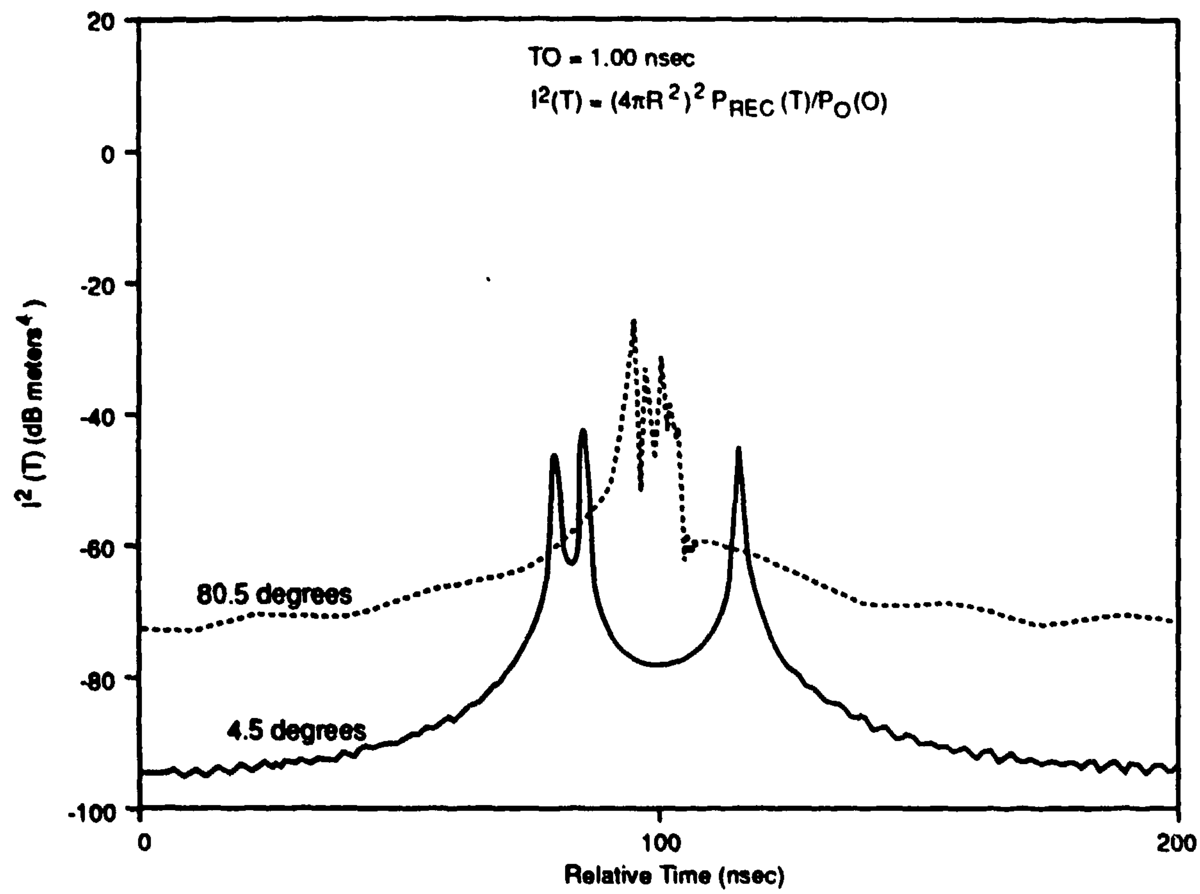
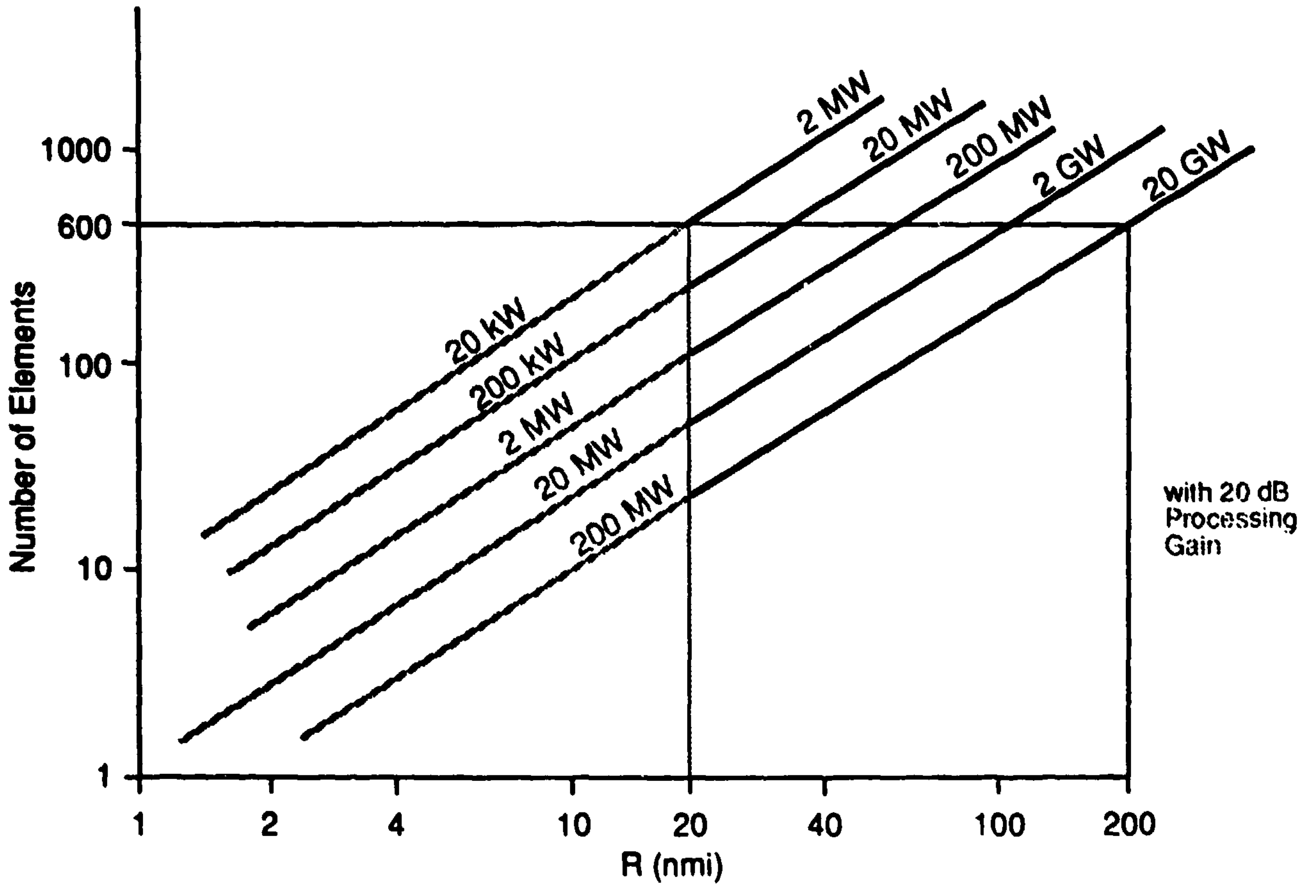


FIGURE H-4. ULTRA-WIDEBAND TIME RESPONSE - SHAPED CRUISE MISSILE



* Nose-on viewing

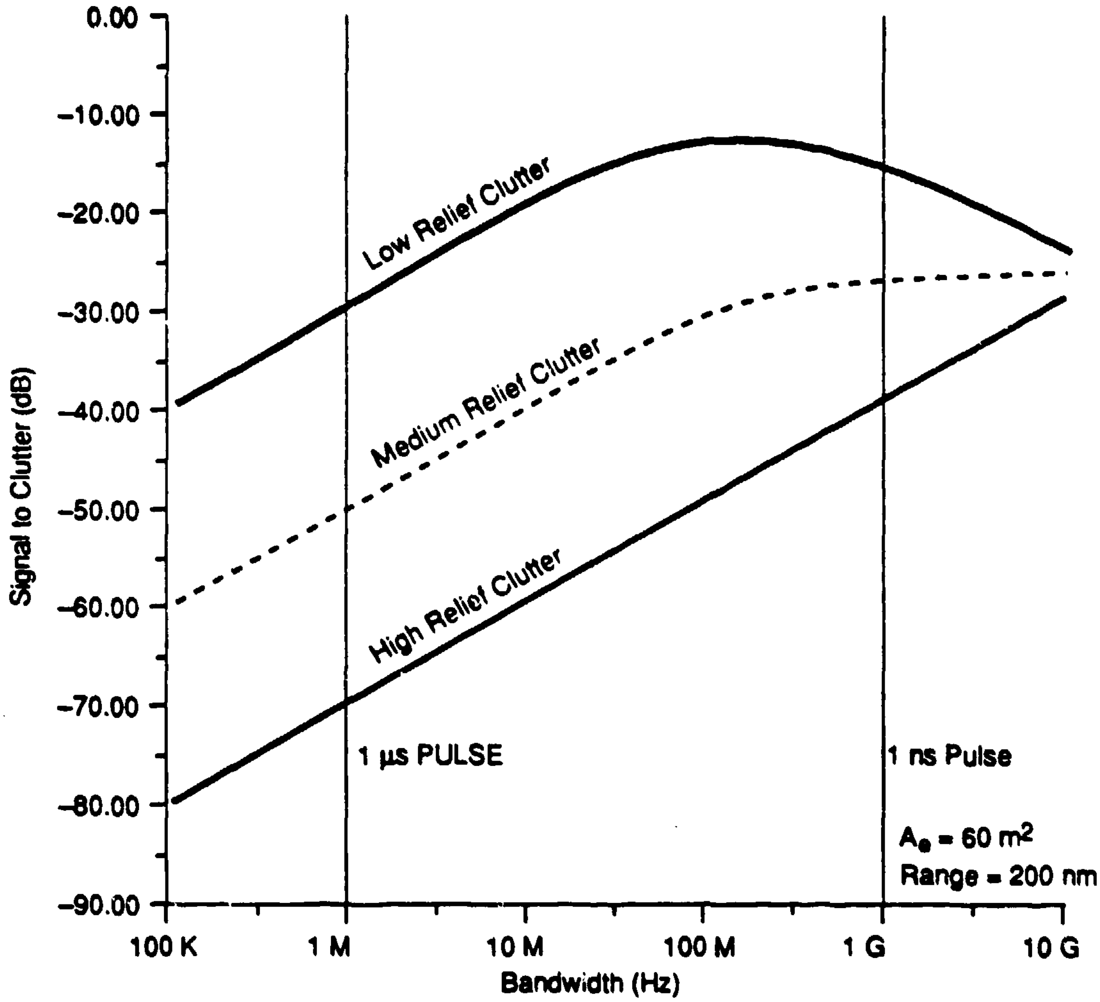
FIGURE H-5. ELEMENT PEAK POWER ESTIMATES (SHAPED CM*)

Figure H-5 shows that for the nominal 600-element array, a prohibitive 2×10^{10} watts per element peak power is required to achieve 200 nmi surveillance range. This includes the requirement to scan 120 degrees in azimuth in 20 sec. Adding coherent integration of 100 pulses, the peak power requirement drops to 2×10^{8} watts per element which could be integrated into a 600-element array. This result points out the need for a more complex waveform to achieve the average power required for surveillance while reducing the peak power to more manageable levels. Note that Figure H-5 also implies that a 20-nmi system can be realized with peak powers which are within the current state of the art.

Clutter Limitations

Clutter is a major limitation to the surveillance performance of airborne radar. Without processing, the clutter return usually far exceeds any anticipated target return. For low PRF waveform, the clutter signal is proportional to the size of the clutter patch within the range-cell of the target. Thus, by increasing bandwidth or decreasing the range-cell width, the signal-to-clutter (S/C) ratio tends to increase.

Figure H-6 shows the increase of the S/C ratio at the 200-nmi maximum range as the bandwidth is increased. The estimates are based on the strawman radar parameters and a Lincoln Laboratory clutter model [2]. Since the clutter area for a 1-GHz-bandwidth radar is 1/1,000 times smaller than that for a 1-MHz-wide narrowband radar, the clutter is shown to decrease by about 25 to 30 dB. However, the chart also shows that even for a 1-GHz radar, additional clutter suppression is needed to achieve acceptable S/C ratios for target detection in high-relief clutter under all clutter conditions. The assumption used in the following calculations is that the clutter level is decreased by increasing bandwidth. There are several factors that might limit the amount of clutter suppression achievable by increased bandwidth [3]. These factors may significantly increase the required clutter suppression which was estimated in this initial study.



Constant Aperture Antenna

Target Type 2, –20 dBsm @ 400 MHz

σ_0 (Medium Relief) = –27 dB

FIGURE H-6. SIGNAL BANDWIDTH EFFECT ON SIGNAL/CLUTTER

An estimate of the mainlobe clutter level for the strawman airborne impulse radar was calculated. It is based on the mainlobe clutter patch area times the clutter reflectivity for medium-relief clutter ($\sigma_0 \simeq -27$ dB). The clutter patch area is the cross range associated with the mainlobe beamwidth, which for an impulse radar having time delay steering is $\Delta\theta = \frac{3cT}{2L}$, times the range resolution $\Delta R = \frac{cT}{2}$. For T = 1 nsec and $\Delta\theta$ = 1.3 degrees, the mainlobe clutter patch area is 2.5 m^2.

For the strawman radar parameters, the mainlobe clutter cancellation requirements were calculated as a function of different target RCS values to achieve a S/C ratio of 14 dB. For a target whose RCS is -20 dBsm, the required clutter cancellation is 38 dB, and for -30 dBsm the cancellation is 48 dB. The 40 to 50 dB clutter suppression might be realizable by highly weighted coherent velocity processors.

For the prescribed low pulse repetition frequency (PRF) waveform, the sidelobe clutter level is primarily associated with clutter in the range ring containing the target. This ring is bounded by the range resolution of the radar. Assuming that only half of the range ring contributes (i.e., the back lobes are considerably lower than the front sidelobes), an estimate is obtained of the sidelobe clutter level for the medium relief clutter (σ_0 = -27 dB). The sidelobe clutter level, σ_C, is $\sigma_0 \pi RcT/2$ which is 350 m^2 at R = 200 nmi. The objective is to achieve S/C = +14 dB as with mainlobe clutter. The required one-way average sidelobe level, a, can be estimated by combining the range equations for the target and the clutter.

$$a = \left[\frac{\sigma_T}{\sigma_C} \quad \frac{1}{S/C_{min}}\right]^{1/2} \tag{2}$$

Table H-1 shows that for detection of targets having σ_T = -20 dBsm, a sidelobe level of -30 dB is required to achieve a minimum S/C ratio of 14 dB as with the mainlobe clutter. For the impulse radar, assuming uniform taper across the antenna array, the one-way average azimuth sidelobe level is 1/N, where N is the number of antenna elements in the azimuth plane. Thus, to achieve a -30 dB sidelobe level, an antenna comprised of 1,000 elements in length would be required.

TABLE H-1. ANTENNA SIDELOBE REQUIREMENTS FOR CLUTTER SUPPRESSION

σ_T(dBsm)	α(dB)	N
-20	-30	1000
-30	-35	3000

For the strawman radar design with an array comprised of only 60 elements, additional clutter suppression on the order of 23 dB is required. This additional suppression could be accomplished by the addition of velocity filters to partition the clutter into approximately 200 velocity resolution cells.

The features of the signal processing needed to achieve velocity filtering of the clutter are much more complex than that required by narrowband radar because a typical target moves through many range gates during the 0.2-sec processing interval. Furthermore, the effect of target motion must be modeled as time dilation rather than a simple Doppler shift. These effects imply that a separate matched filter is required for each velocity interval processed by the radar. For a 0.5-ft range resolution (1-nsec pulse), we estimate a 1×10^{11} operations/sec throughput for the 2 million range gates, each having 100 velocity filters, to cover a 150-nmi range interval. Implementation of this signal processor will require ultra-fast A/D converters (8 bits at 3 GHz), which are currently beyond the state of the art.

Impulse Transmitter Interference

The high peak power transmitted by an impulse radar for this application creates an interference problem. The low-power systems used for soil penetration studies or intrusion systems do not cause appreciable problems with other electromagnetic (EM) spectrum users. However, the high peak power requirements and continuous operation for long-range surveillance spread over 1 GHz bandwidth or greater dramatically increase the receiver noise floor above (KTB) for any other spectrum user in the vicinity of the transmitting impulse radar.

Figure H-7 shows the increase in receiver noise floor (in dB) for an ultra-high frequency (UHF) receiver (or, for that matter, any other in the 100 to 1,000 MHz band) having a bandwidth of 3 kHz, a 0-dB sidelobe antenna gain, and a 3-dB noise figure (NF). The chart shows that the strawman airborne radar having a peak power of about 120 GW (for 20-dB integration gain) would cause at least a 10-dB increase in receiver noise floor to any spectrum users within line-of-sight of the radar. Front-end limiters could be used to reduce the interference. However, the feasibility of making these changes for all users of the 100-MHz to 1-GHz band is highly questionable.

Conclusions

Calculations based upon a strawman model for a (UWB) impulse radar show that the use of short pulses on the order of 1 nsec in duration is not feasible for long-range (~200 nmi) surveillance, owing to the extremely high peak powers which are required by this approach. Although the use of short pulses reduces the ground clutter level by several orders of magnitude over systems with megahertz bandwidths, an additional reduction of clutter by a factor of about 10,000 is required in order to detect cruise-missile-sized objects. This clutter reduction can theoretically be obtained by discriminating ground from target returns on the basis of time dilation effects using a bank of velocity matched filters. This requires a processor capable of 1×10^{11} operations/sec, as described above.

Although the Red Team assessment was primarily focused on the utility of impulse radar for long-range Air Defense applications, there are other applications for this technology that may benefit from the ability to inexpensively generate a low-power, ultra-wideband pulse. Potential applications include:

- Barrier sensor
- Point surveillance

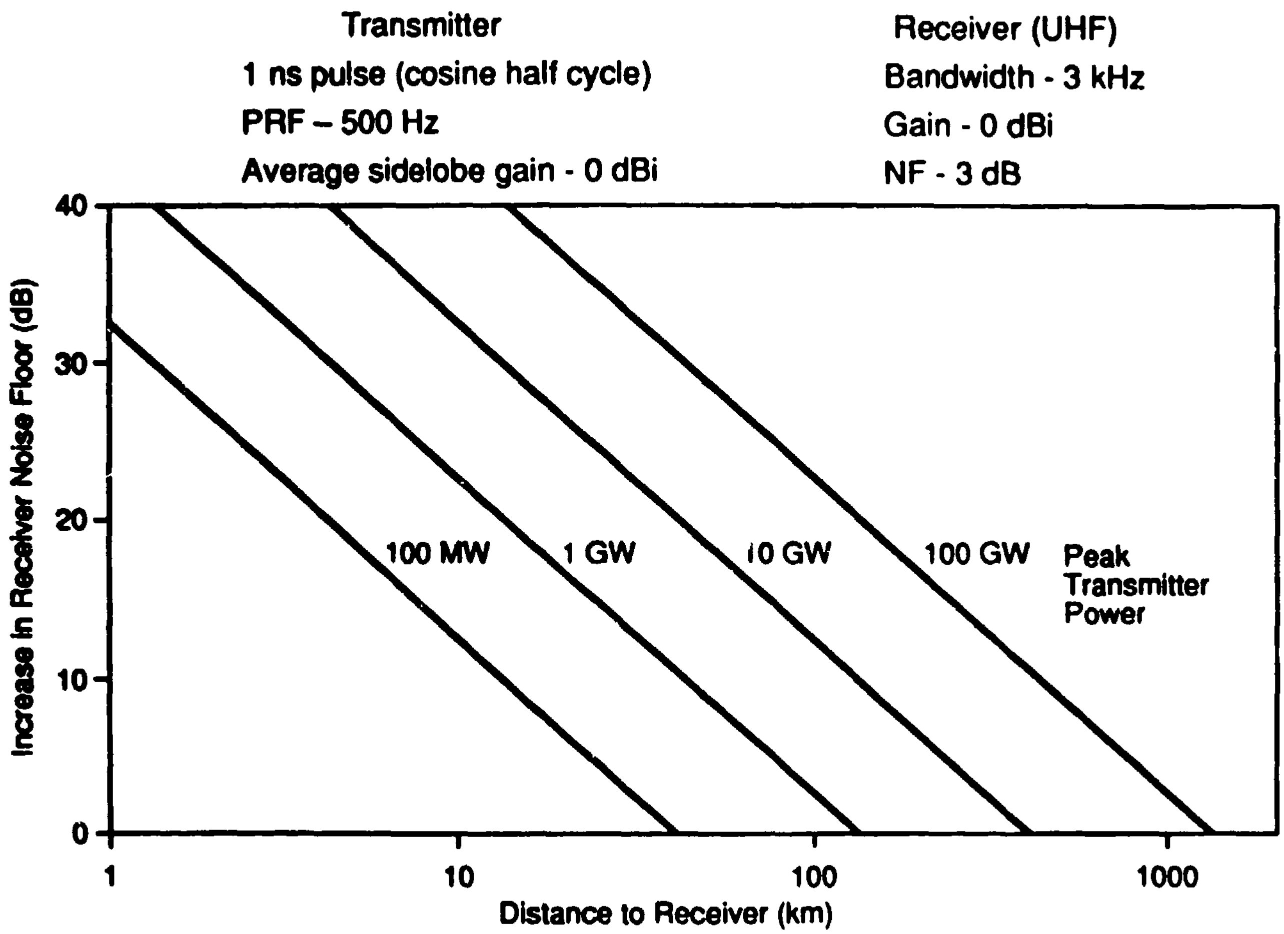


FIGURE H-7. ELECTROMAGNETIC INTERFERENCE CAUSED BY TRANSMITTER OF IMPULSE RADAR

- Foliage penetration
- Identification
- Covert communications.

A credible assessment of each of these applications would require a systematic examination of strawman designs, as done here, to identify the technical issues and establish the advantage of an impulse radar versus other, more conventional, alternatives.

A pervasive problem for UWB broadcasting systems is the fact that they share spectrum with a large number of critical military and civilian services (UHF, VHF, voice communications, cellular telephone, TV and FM broadcasting, for example). As such, they are susceptible to interference from these services, and they could potentially interfere with them. The problem has been managed in the laboratory for short-range radar and communication systems; however, the long-range wide area surveillance radar requiring perhaps 10 million times as much effective radiated power (ERP) makes the electromagnetic interference (EMI) problem effectively insurmountable.

The value of UWB short pulses, compared to more conventional spread spectrum techniques, is dependent on the possibility of reducing the effectiveness of radar absorbing materials. For highly shaped objects such as cruise missiles, the potential enhancement by the use of very short pulses is probably less than 10 dB. To date, there is no evidence that the interaction between short UWB pulses and radar absorbing material cannot be predicted by conventional sinusodial (CW) measurements of amplitude and phase combined with Fourier theory. Barring experimental evidence to the contrary, the advantages of short pulses are due to bandwidth rather than waveshape and may, therefore, be achieved with pulse compression or spread spectrum waveforms of identical band occupancy. Since these waveforms may be easier to generate than short pulses at the high average power required for long-range surveillance, the selection of the appropriate waveform should be made by the appropriate engineering trade-off study.

Acknowledgement

The authors wish to thank David Lamensdorf for carrying out the calculations of the short pulse response and for assisting in the preparation of the paper.

REFERENCES

[1] Kramer, J. D. R. et al., "Ultra-Wideband Radar Applicability to Air Defense - Red Team Assessment", MITRE Technical Report M90-18, March 1990.

[2] Billingsley, J. B., "Ground Clutter Measurements for Air Defense Radar", Lincoln Laboratory Report #786, November 1987.

[3] Davis, C. W. III et al., "Characteristics of Ultra Wideband Radars Pertinent to Air Defense Surveillance" (Ultra Wideband Radar Symposium Proceedings, 1990).

APPENDIX I

COMPARATIVE DESIGNS OF IMPULSE AND CONVENTIONAL APPROACHES

APPENDIX I

COMPARATIVE DESIGNS OF IMPULSE AND CONVENTIONAL APPROACHES

[Contributed by Larry Lynn[1]]

The Review Panel saw a need to undertake point designs of radars for some specific applications and identified four such applications where there appeared to be potential implementation advantages for the impulse radar approach. The selection was based on the combined requirement for low frequency and high resolution with a bias toward shorter ranges since earlier analyses suggested that, at longer ranges, the implementation tended to become quite similar.

The objective of the conceptual design studies recommended is to take the first step toward determining whether impulse radar techniques might offer implementation advantages over conventional UWB approaches in any military applications. The conclusion is certainly not clear and no such implication should be drawn. There is currently inadequate basis for any conclusion.

Neither should it be anticipated that a conclusion will be possible at the end of these studies. The best that can be expected is that impulse techniques might continue to offer potential advantage, in which case further steps should be taken as outlined in Section IX-A. If the advantage is clearly with conventional UWB in all cases, further work on impulse techniques for these kinds of applications would not be warranted.

The intent of this Appendix is to define the trade-offs and issues which must be examined for each of the potential applications. The four cases, discussed separately in the following sections, are as follows:

- Short-range, ground-based, moving target detection radar penetrating foliage and walls
- Short-range airborne imaging radar for foliage penetration

---

[1]Atlantic Aerospace Electronics Corporation

- Ground-based, air defense radar with non-cooperative target ID
- Radar for point defense against sea skimmers.

The first two applications are excellent candidates for impulse implementation. A study of the other two applications is needed to understand the contribution such techniques can make to special air-defense needs. Applications to any longer-range systems should await the results of these studies before further resources are expended.

The recommendation of the Panel is that the Government select objective investigators to undertake these analyses at a level of approximately 1 to 2 person-years per application, specify a detailed analysis covering all issues as outlined below, and subject the results to review by independent experts. Only with such analysis can the real issues of implementation advantage be illuminated and understood.

For each application, the investigator should be directed to design the conventional UWB radar based on scaling current designs or, where desirable, using conventional techniques to achieve low frequency and wide bandwidths. The design of the impulse radar should be done with optimum choices of frequency and waveform. In both cases, the design should be optimized to perform according to the specifications of that system and with all of the issues and trade-offs considered. As a minimum, the end result should include

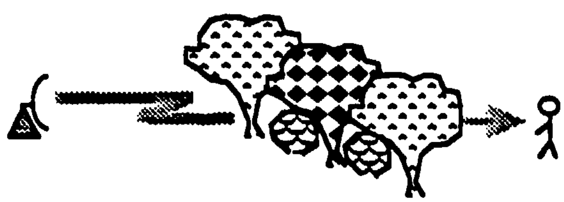
- Complete block diagram including transmitter, antenna, power supplies, receiver, signal and data processing, and all ancillary equipment necessary for stand-alone operation.
- Aperture designs and sizes.
- "Sizing" of each block with all the relevant parameters (e.g., some detail of the receiver, its noise figure, signal processing, data processing, data rates, bandwidths, etc.)
- Estimates of relative size, weight, prime power, and cost and corresponding rationales.

- Exposure of all assumptions, techniques, etc.
- Complete discussion of all issues and how they were treated.

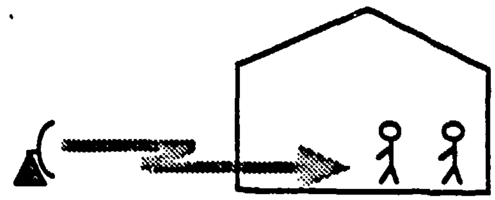
The criteria for comparison would be weight, size, prime power, and cost.

<u>Short-Range, Ground-Based, Moving Target Detector Penetrating Foliage, Walls</u>

INTRUSION DETECTION THROUGH FOLIAGE



MOTION DETECTION & IMAGING THROUGH WALLS



The radar(s) can perform these functions separately or in the same design but should be based on the following "specifications":

For intrusion detection through foliage,

- 180-degree search coverage
- 300-meter range (longer is desirable) through moderate tropical jungle foliation typical of Panama
- 1 mm/hr rain and dampness on foliage
- Detection of crawling or walking personnel
- Localization to ≲10 meters in range and cross range
- No concern for jamming.

For motion detection and imaging through walls,

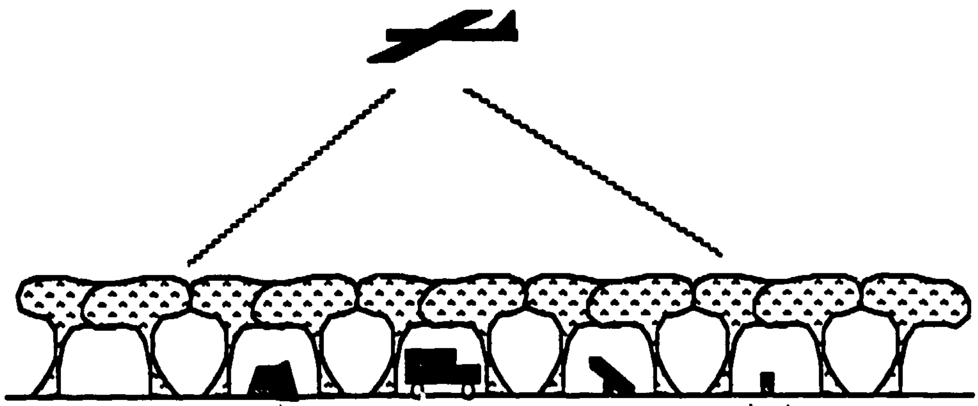
- 20-degree search coverage
- 150-meter range with light to medium foliage between the radar and the wall
- Detection of moving or nearly stationary personnel
- Localization to ≤5 meters in range and cross range
- No concern for jamming.

The issues which require special attention in trade-offs and analyses, aside from the general design, include the following:

- Clutter rejection needs and issues
- EMC issues *vis a vis* other systems nearby
- Detectability of the signals for cases where the use of the radar is intended to remain covert
- Ability to image personnel who were detected in motion and have then stopped.

A variation on this class of system which could be of interest in a very important and unsolved problem is mine detection. Generally, the problem is not actually detection but rather discrimination of mines from the underground clutter.

Short-Range Airborne Imaging Radar for Foliage Penetration



The following "specifications" describe the scenario against which both impulse and "conventional" radar designs should function:

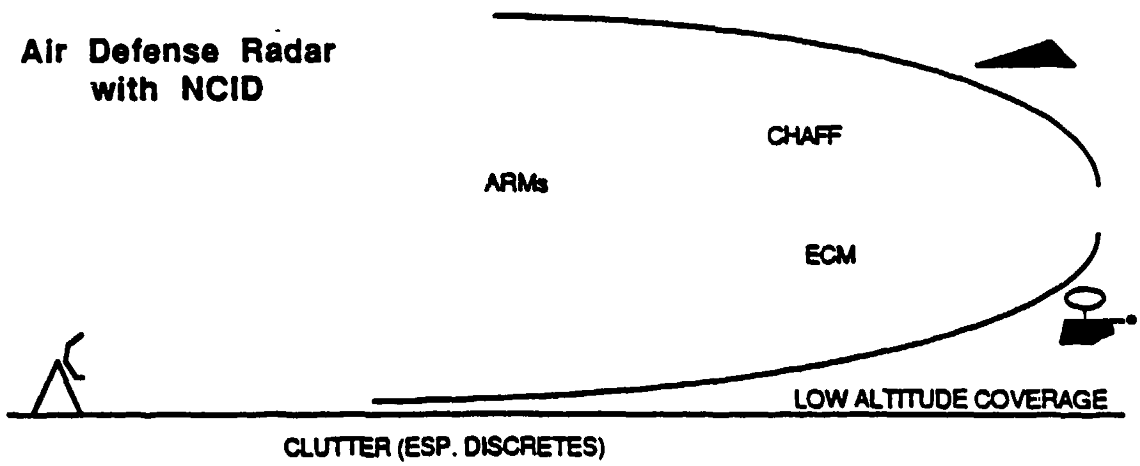
- Tropical jungle canopy (Case 1) and typical northern Canada mixed deciduous and conifer forest (Case 2).
- Rain up to 1 mm/hr and consequent dampness in foliage
- Radar altitude of 3 km (UAV)
- Depression angles 20-60 degrees
- Targets are trucks, TELs and other military targets
- Clutter: trees, rural man-made objects and buildings
- Search swath should be a maximum and no less than ±5 km
- $P_d = 0.9$ and $P_{fa} = 0.001$/km after target classification by imaging.

The issues which require special attention in trade-offs and analyses, aside from the general design, include the following:

- Frequency choice trade-offs for target response, foliage attenuation, clutter response, atmospheric attenuation, background noise, system noise, transmitter/antenna efficiency, beamwidth (angular resolution), sidelobe levels, transmitter coherence, foliage/earth phase perturbation (coherence).

- ECM vulnerability
- Clutter rejection needs and issues
- Detectability of the signals for cases where the use of the radar is intended to remain covert
- Bandwidth/range resolution.

Ground-Based Air Defense Radar with NCID



The following "specifications" describe the scenario against which both impulse and "conventional" radar designs should function:

- Full 360-degree search for altitudes ≤3 km; Track while scan
- Cumulative $P_d = 0.5$ with $P_{fa} = 10^{-6}$ at range of 20 km
- Targets:
  - Velocity = 0 to M1.5, acceleration ≤4 g, update period ≤2 sec
  - Hovering helicopters behind tree lines
  - Include RCS: use "canonic low RCS target" at secret level

- Environment: Typically near FLOT in medium intensity conflict (bears on EMC, ARM issues in terms of other equipments in vicinity). Rain 2 mm/hr.

- Clutter: Rural, tropical foliation, miscellaneous vehicles, junk, and rural buildings

- Threats, considered one at a time:

  - 1-kW ERP (average) airborne jammer using energy with reasonable understanding of radar (R = 40 km)

  - ARM designated for general class of radars (i.e., either conventional or impulse class) but not against specific radar

  - Chaff designed against the general band of the radar

- NCID can either be a mode called up after a target has been detected or can be inherent all the time during search. There is no preference.

The issues which require special attention in trade-offs and analyses, aside from the general design, include the following:

- NCID capabilities with consideration for the use of high-range resolution (i.e., imaging in range, perhaps in 2-D, but separate if this is considered) and resonance effects (target body resonance and possibly localized resonances). No other NCID effects should be included unless it is demonstrated that these are inherently appropriate for one of impulse or "conventional" and not for the other.

- Effective RCS of resolved targets.

- Energy considerations and need for multiple pulse integration.

- Clutter rejection needs, techniques, and issues. What does clutter look like? If clutter spectrum center is less than 100 MHz, is the clutter reflectivity lower?

- Angular resolution and accuracy required.

- EMC issues *vis a vis* other nearby systems

- Performance degradation in the presence of jamming, considering jammer use of its power in all forms of jamming including barrage and deception modes. Define the optimum approach to jamming each radar and analyze that radar's performance against that optimum jamming strategy. Include serious look at how sidelobe cancellation and similar ECCM would be incorporated in each UWB form.

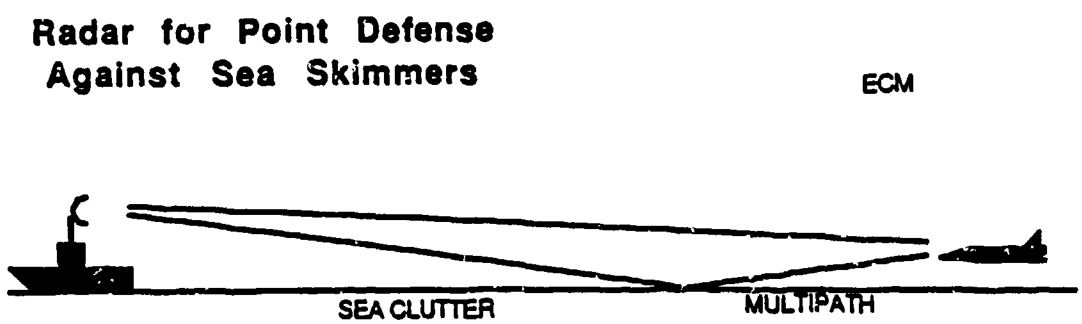
- Relative performance against chaff.

- Low altitude coverage.

- Performance against very low helicopters including one hovering behind a tree line.

- Relative vulnerability to ARMs.

<u>Radar for Point Defense Against Sea Skimmers</u>



The following "specifications" describe the scenario against which both impulse and "conventional" radar designs should function:

- Full 360-degree search for altitudes ≤ 0.5 km

- Track while scan

- Cumulative $P_d = 0.5$ with $P_{fa} = 10^{-6}$ at range of 15 km

- Targets:

  - Velocity $\leq$M3

  - Include RCS: use "canonic low RCS target" for cruise missiles at secret level

- Altitude: 2 meters

- Environment and clutter: Sea state 1 and 4 (examine for both). Rain ≤2 mm/hr.

- Threat: 10-kW ERP (average) airborne jammer using energy with reasonable understanding of radar (R = 100 km)

- Radar Height: 20 meters.

The issues which require special attention in trade-offs and analyses, aside from the general design, include the following:

- Multipath and low-altitude coverage issues. Analyze in some depth and consider whether multipath mitigation/compensation is possible.

- Clutter rejection needs and issues. Sea clutter spikes.

- Angular resolution and accuracy required

- Performance degradation in the presence of jamming, considering jammer use of its power in all forms of jamming including barrage and deception modes. Define the optimum approach to jamming each radar and analyze that radar's performance against that optimum jamming strategy.

- ECM effects in the presence of other similar radars on nearby ships and, where appropriate, quantitatively estimate the number of radars which can reasonably operate in the same vicinity (e.g., degradation of each in the presence of N others using the same general band). Include serious look at how sidelobe cancellation and similar ECCM would be incorporated in each UWB form.

- Relative vulnerability to ARMs.

APPENDIX J

ON TIME DIVERSITY USING AN ULTRA-WIDEBAND RADAR

APPENDIX J

ON TIME DIVERSITY USING AN ULTRA-WIDEBAND RADAR

[Contributed by Eli Brookner[1]]

1.0 SUMMARY

Diversity of Eight

It has been contended that ultra-wideband time diversity can provide improved detectability of a target in clutter. Ultra-wideband time diversity is obtained by having the slant range resolution of the ultra-wideband radar be much smaller than the slant range extent of the target. The best time diversity is achieved when the slant range resolution of the ultra-wideband radar is 1/8 of that of the range extent of the target for the nosie dominant case. Such a resolution shall be assumed for the ultra-wideband radar in this discussion. (Results are also given for a better resolution--1/100th target extent.) Its performance is compared to that of a standard coarser range resolution system, one for which the range resolution is equal to the target extent, thus its slant range resolution is 8 times worse than that for the ultra-wideband radar. For the coarser range resolution system a frequency diversity of 8 shall be used.

For a homogeneous target, ultra-wideband time diversity would indeed result in a better ability to detect a target in clutter. However, the same performance in clutter can be achieved using the coarse resolution with frequency diversity. For a homogeneous Swerling-2 target, the clutter can be increased by about 14 dB if either ultra-wideband time diversity or coarse resolution with frequency diversity is used. For a homogeneous nonfluctuating target, the increase is 7 dB for both types of diversity.

For a Swerling-2 nonhomogeneous target, specifically one whose scattering is concentrated in one range resolution cell of the ultra-wideband

1 Raytheon

radar (whose resolution is 1/8 of the target range extent), ultra-wideband time diversity results in worse performance (by 5 to 7 dB) in clutter than does the standard coarser resolution system with frequency diversity. For the nonfluctuating nonhomogeneous target, essentially the same performance in clutter is achieved with an ultra-wideband time diversity system or a standard system using coarser resolution and time diversity.

It was found that ultra-wideband time diversity offers no advantage over standard coarser resolution system with frequency diversity relative to radar noise sensitivity. In fact, it gives poorer radar sensitivity (by 5 to 7 dB) for a Swerling-2 nonhomogeneous target. The results in the above paragraphs are summarized in Tables 1 through 4.

Diversity of 100

For a diversity of 100, again there is no advantage of time diversity over frequency diversity (having coarse resolution) for the Swerling-2 homogeneous target regarding clutter rejection for the clutter dominant case. For the Swerling-2 nonhomogeneous target, it is better to use frequency diversity with coarse resolution rather than ultra-wideband time diversity for clutter robustness (by 3 to 8 dB). For the nonfluctuating homogeneous target, there is no advantage of using time or frequency diversity of 100. If the target is nonhomogeneous, time diversity offers a 5 dB advantage in robustness against clutter if the optimum matched receiver is used. If the receiver matched to the homogeneous target is used, this advantage disappears. This is not felt to be a sufficient advantage to warrant the use of a resolution 1/100th the target extent. It is felt that the enemy would not have his low-cross-section target consist of one large scatterer, he would tend to have such a large scatterer reduced to the size of the others. Finally, better clutter suppression than offered by the ultra-wideband (of 5 dB when 1/100th the target extent resolution is used) could be obtained with frequency diversity using coarse resolution and Doppler processing (on the order of tens of dB clutter suppression). These results are summarized in Table 5.

Final Comments

It has also been contended that the different band echoes of an ultra-wideband pulse can be coherently added to provide better radar sensitivity. This is not possible. The different echoes for the different frequency bands are phase incoherent relative to each other, just as are the echoes from the different point scatterers of a target whose extent is larger than the radar range resolution. The detailed analyses that led to the above conclusions are now given.

2.0 TIME DIVERSITY THROUGH ULTRA-WIDEBAND RADAR

2.1 No Clutter Present

The case where clutter is not present, or at least where the clutter is about 10 dB lower than the receiver thermal noise, is analyzed. This is the simpler situation.

2.1.1 Homogeneous Target

The use of ultra-wideband time diversity will improve the target detection sensitivity for a homogeneous Swerling-2 target. However, the same improvement can be achieved by using the standard coarse resolution radar that employs frequency diversity. The decrease in the energy required per dwell for the radar is 4.9 dB when either the ultra-wideband time diversity is used or the standard frequency diversity is used for a homogeneous Swerling-2 target; see Table 3. For both cases, a diversity of 8 was assumed as indicated in the above summary section. Furthermore, as discussed previously, for the ultra-wideband radar, the time diversity was obtained by having the slant range resolution equal to 1/8 of the target extent in slant range; the frequency diversity by using 8 frequencies and a slant range resolution equal to that of the target extent.

For a nonfluctuating target, using ultra-wideband time diversity will only decrease the target detectability, albeit by only a small amount, 1.8 dB; see Table 3.

2.1.2 Nonhomogeneous Target

If the scattering from the target is dominated by the return from only one range resolution cell for the ultra-wideband radar, then using time diversity will decrease the target detectability for a Swerling-2 target, this decrease being between 0.5 and 1.8 dB; see Table 3. For a nonfluctuating target, the decrease would also be between 0.5 and 1.8 dB.

2.2 Clutter Present

Here it is assumed that the clutter is the dominant interference in the receiver, it being at least 10 dB greater than the receiver thermal noise level.

2.2.1 Clutter Robustness

Homogeneous Target

Table 4 shows that, for a homogeneous target having Swerling-2 statistics, the allowable background clutter can be increased by 13.9 dB when either ultra-wideband time diversity is used (of a factor of 8) or frequency diversity is used (of a factor of 8). For a homogeneous target having nonfluctuating statistics, the increase is 7.2 dB for either ultra-wideband time diversity or standard coarser resolution with frequency diversity.

The table also indicates that the radar noise sensitivity improves by 4.9 dB for the homogeneous Swerling-2 target when either time diversity or frequency diversity is used. This is the increase in sensitivity needed to keep the thermal noise 10 dB below the allowable clutter level, so that the system is clutter limited.

For the case of a homogeneous nonfluctuating target, the ultra-wideband time diversity offers no target detection sensitivity advantage, it actually results in a loss of sensitivity of 1.8 dB; frequency diversity results in a 1.7-dB loss. When the target is nonfluctuating, the best radar sensitivity with respect to thermal noise is obtained when no diversity at all is used; see Table 4.

Nonhomogeneous Target

If the target has Swerling-2 statistics and is nonhomogeneous, that is, the echo from the target is dominated by the return from one range resolution cell, then using ultra-wideband time diversity will result in a potential increase in the allowable background clutter by 7.2 or 8.5 dB depending on the type of receiver processing; see Table 4. The latter results when no video integration is used from cell to cell across the target, whereas the former assumes that a video integration of all 8 cells across the target is used. With a standard coarse resolution and frequency diversity, the allowable clutter increase would be the original 13.9 dB for the nonhomogeneous target, just as it was for the homogeneous target; see Table 2. Thus, it is better to use coarse resolution with frequency diversity for the nonhomogeneous Swerling-2 target.

For the nonfluctuating homogeneous target, the allowable increase in the background clutter level is again 7.2 dB or 8.5 dB for the same two respective cases indicated previously; see Table 4. Almost the same result is obtained if the standard coarse resolution system is used with a frequency diversity of 8, the allowable increase being 7.2 dB in the clutter level; see Table 4.

2.2.2 Target Detection Sensitivity Against Thermal Noise

Homogeneous Target

Table 2 also shows that ultra-wideband time diversity can increase the target detection sensitivity relative to thermal noise by 4.9 dB for the homogeneous Swerling-2 target. However, the same result is obtained for the standard coarse resolution radar using frequency diversity.

If the target is nonfluctuating and nonhomogeneous, then the transmitted energy required for the same detectability increases by about 1.8 dB when ultra-wideband time diversity or frequency diversity is used.

Better noise sensitivity performance is obtained if no diversity is used for the nonfluctuating target; see Table 4.

Nonhomogeneous Target

If the target is nonhomogeneous and ultra-wideband time diversity is used, then the detection sensitivity relative to thermal noise is poorer by 1.8 and 0.5 dB, respectively, for the cases mentioned previously, independent of whether the target is fluctuating or nonfluctuating. As for the nonfluctuating homogeneous target, better noise sensitivity is achieved for the nonfluctuating nonhomogeneous target if no time or frequency diversity is used. However, the clutter performance would then be worse. The choice of the use of diversity would depend on which is the driver, the clutter suppression or the noise sensitivity. Typically, for a coarse resolution system the design of the system would be made such that the thermal noise is dominant rather than the clutter.

2.3 Coherent Addition of Different Frequency Components of the Ultra-Wideband Radar Pulse

The different frequency components of the ultra-wideband pulse echo would be phase incoherent from each other because they result from scattering from different phase centers of the target, the target phase center varying with carrier frequency. Another way to think of this is that the independence from frequency to frequency is the basis for frequency diversity.

TABLE J-1.

ULTRA-WIDEBAND TIME DIVERSITY VERSUS CONVENTIONAL COARSE RESOLUTION WITH FREQUENCY DIVERSITY: SWERLING-2-TARGET

- **ROBUSTNESS AGAINST CLUTTER**
  - **HOMOGENEOUS TARGET: SAME IMPROVEMENT FOR BOTH (14 dB)**
  - **NONHOMOGENEOUS TARGET: 5 TO 7 dB WORSE PERFORMANCE WITH ULTRA-WIDEBAND TIME DIVERSITY THAN WITH COARSE RESOLUTION AND FREQUENCY DIVERSITY**
- **SENSITIVITY AGAINST RECEIVER THERMAL NOISE**
  - **HOMOGENEOUS TARGET: SAME IMPROVEMENT FOR BOTH (5 dB)**
  - **NONHOMOGENEOUS TARGET: SLIGHTLY WORSE PERFORMANCE (UP TO 2 dB) OBTAINED WITH TIME DIVERSITY THAN WITH NO TIME DIVERSITY. BETTER OFF (By 5-7 dB) WITH FREQUENCY DIVERSITY THAN WITH TIME DIVERSITY**

TABLE J-2.

ULTRA-WIDEBAND TIME DIVERSITY VERSUS CONVENTIONAL COARSE RESOLUTION WITH FREQUENCY DIVERSITY: NONFLUCTUATING (MARCUM) TARGET

- **ROBUSTNESS AGAINST CLUTTER**
  - **HOMOGENEOUS TARGET: SAME IMPROVEMENT FOR BOTH (7 dB)**
  - **NONHOMOGENEOUS TARGET: SLIGHT BETTER PERFORMANCE (ABOUT 1 DB) WITH ULTRA-WIDEBAND TIME DIVERSITY THAN WITH COARSE RESOLUTION AND FREQUENCY DIVERSITY**
- **SENSITIVITY AGAINST RECEIVER THERMAL NOISE**
  - **HOMOGENEOUS TARGET: WORSE PERFORMANCE OBTAINED WITH TIME OR FREQUENCY DIVERSITY (UP TO 2 dB) THAN WITH NO DIVERSITY**
  - **NONHOMOGENEOUS TARGET: SLIGHTLY WORSE PERFORMANCE (UP TO 2 dB) OBTAINED WITH TIME DIVERSITY THAN WITH NO TIME DIVERSITY. BETTER OFF WITHOUT TIME OR FREQUENCY DIVERSITY (UP TO 2 dB)**

TABLE J-3. TIME VS. FREQUENCY DIVERSITY: NO CLUTTER PRESENT (OR THERMAL NOISE DOMINANT); DIVERSITY OF 8

Type Diversity	Type Fluctuating Target	Type Cross-Section Distribution for Target	Video Integration Used	Relative Energy Needed for Detection (dB)
None	Swerling-2	--	None	0 (Ref. for Swerling-2 Target)
Time		Homogeneous	8	-4.9
		One Target Cell Dominant	None	+0.5
			8	+1.8
Frequency		--	8	-4.9
None	Non-Fluctuating (Marcum)	--	None	0 (Ref. for Marcum Target)
Time		Homogeneous	8	+1.8
		One Target Cell Dominant	None	+0.5
			8	+1.8
Frequency		--	8	+1.8

Assumptions:

(1) Time Diversity: Ultra-wideband pulse having range resolution equal to 1/8th of target range extent.

(2) Frequency Diversity: Coarse slant range resolution equal to target extent. Frequency diversity of 8.

(3) $P_d = 90\%$, $P_f = 10^{-6}$.

TABLE J-4. TIME VS. FREQUENCY DIVERSITY: CLUTTER DOMINANT CASE; DIVERSITY OF 8

Type Diversity	Type Fluctuating Target	Type Cross-Section Distribution for Target	Video Integration Used	How Much Clutter Can Increase (dB)	Relative Energy Needed for Detection (dB)
None	Swerling-2	--	None	0 (Ref. for Swerling-2 Target)	
Time		Homogeneous	8	13.9	-4.9
		One Target Cell Dominant	None	8.5	+0.5
			8	7.2	+1.8
Frequency		--	8	13.9	-4.9
None	Non-Fluctuating (Marcum)	--	None	0 (Ref. for Marcum Target)	
Time		Homogeneous	8	7.2	+1.8
		One Target Cell Dominant	None	8.5	+0.5
			8	7.2	+1.8
Frequency		--	8	7.2	+1.7

Assumptions:

(1) Time Diversity: Ultra-wideband pulse having range resolution equal to 1/8th of target range extent.

(2) Frequency Diversity: Coarse slant range resolution equal to target extent. Frequency diversity of 8.

(3) $P_d = 90\%$, $P_{fa} = 10^{-6}$.

(4) Clutter 10 dB greater than thermal noise.

TABLE J-5. TIME VS. FREQUENCY DIVERSITY: CLUTTER DOMINANT CASE; DIVERSITY OF 100

Type Diversity	Type Fluctuating Target	Type Cross-Section Distribution for Target	Video Integration Used	How Much Clutter Can Increase (dB)	Relative Energy Needed for Detection (dB)
None	Swerling-2	--	None	0 (Ref. for Swerling-2 Target)	
Time		Homogeneous	100	22.1	-2.1
		One Target Cell Dominant	None	19.0	+1.0
			100	14.4	+5.6
Frequency		--	100	22.1	-2.1
None		--	None	0 (Ref. for Marcum Target)	
		Homogeneous		14.4	+5.6
		One Target Cell Dominant	None	19.0	+1.0
				14.4	+5.6
Frequency		--		14.4	+6.6

Assumptions:
(1) Time Diversity: Ultra-wideband and pulse having range resolution equal to 1/100th of target range extent.
(2) Frequency Diversity: Coarse slant range resolution equal to target extent. Frequency diversity of 100.
(3) $P_d = 90\%$, $P_{fa} = 10^{-6}$.
(4) Clutter 10 dB greater than thermal noise.

APPENDIX K

ABSORBER MEASUREMENTS CONTRASTING ULTRA-WIDEBAND INSTANTANEOUS AND SWEPT FREQUENCY TECHNIQUES

APPENDIX K

ABSORBER MEASUREMENTS CONTRASTING ULTRA-WIDEBAND INSTANTANEOUS AND SWEPT FREQUENCY TECHNIQUES

[Contributed by J. Pete Hansen[1]]

Introduction

Continuing interest in the wideband response of microwave absorbers has led to the posing of two fundamental questions: (1) What are the actual time domain waveforms produced when an ultra-wideband RF signal (nominal one to five cycles of a given RF frequency) reflects from a typical absorber?, and (2) Can we predict this time domain response based on multiple complex phase and amplitude responses measured at individual CW frequencies across the band of interest? The second question is dependent on the linearity of the materials and on the absence of hysterisis effects or energy storage mechanisms. If non-linear effects, as would be generated by a diode, are not present and there are no hysterisis or energy storage mechanisms, then CW point-by-point complex phase and amplitude measurements should be sufficient to construct valid time domain responses.

Approach

An obvious approach to answering these questions is to perform both ultra-wideband pulse measurements and complex, point-by-point frequency measurements of the same absorber and then compare the results in both the time and frequency domains. In the case of direct pulse measurements, the recorded time domain waveforms may be analytically processed to provide frequency values. In the case of complex CW measurements, the frequency domain data can be windowed and analytically transformed into a time domain waveform. It is postulated that the results from these two types of

[1]Naval Research Laboratory

measurements will differ only if non-linearities, hysterisis, or energy storage mechanisms are present.

Experiment

The experimental measurement facility shown in Figure K-1 was configured to conduct side-by-side direct pulse and complex CW reflection measurements of microwave absorbers. The pulse measurement utilized a 60-psec, 10-V pulse generator as a source. This basic source was then filtered by selected microwave transitions to form multiple-cycle RF signals with center frequencies in the S- to X-band regions and with envelopes with durations on the order of 0.4 nsec. These signals were transmitted and received by dual wideband ridge guide horns. The basic target was a square metal plate, 15 cm on a side, situated 0.5 m from the face of the horn antennas. The illumination angle was perpendicular to the surface of the plate (with the horns slightly squinted to place overlapping beams on the plate). Reflected signals were sampled by a wideband digital sampling oscilloscope with a nominal receive bandwidth of DC to 15 GHz. The time domain waveform was in turn recorded and analyzed by a second digital oscilloscope with an FFT processor to provide frequency analysis of the received spectrum (125-point power spectrum with rectangular window).

Complex (phase and amplitude) CW measurements were conducted with the same microwave horns, cables, and targets. Phase coherent, harmonically related CW signals were individually transmitted and received by a vector network analyzer. The transmitted signals were power leveled at 0 dBm peak at the antenna input across a nominal 15-GHz bandwidth. Individual received values (phase, amplitude) were time windowed and analytically convolved by an internal processing program in order to form derived time domain waveforms.

For this experimental setup, primary comparisons were made in the time domain by examining the direct pulse waveform and the derived CW waveform. It should be pointed out that the receive bandwidths of the sampling oscilloscope and the network analyzer were not fully matched. In addition, the instantaneous power spectrum of the direct pulse provided to the transmit horn was tapered by the microwave transitions while the individual CW signals provided by the network analyzer were at equal peak powers. These mismatches contributed to some differences between calibration signals recorded for the bare metal plate for the pulse and CW measurements. It was decided to not analytically correct for the differences.

There were also obvious near- and far-field problems in the experiment geometry, as well as contributing reflections from the target edges. All of these effects were assumed to be linear and equally perturbing to each type of measurement.

Absorber Measurements

Approximately twelve different types of absorbers designed for regions in the nominal 2- to 15-GHz RF frequency band have been tested in the experimental facility. The following series of data for an S-band and an X-band absorber are representative

Example #1: An S-Band Absorber

Figure K-2 shows the (manufacturer-generated) absorber power response of a typical S-band tuned absorber. Note the attenuation peak at approximately 3 GHz with a nominal attenuation through the rest of the test band. Figure K-3 illustrates direct pulse measurements of this absorber as taken with the test facility. For this series of data, the top display shows the calibration waveform received when the transmit antenna is pointed directly into the receive antenna. The full time scale of the RF voltage window is 1 nsec. The top right display shows the derived power spectrum of the time waveform. The peak of the spectrum is around 3 GHz, as predicted by the approximate wavelength of the RF voltage. The middle left display shows the calibration waveform received for reflection from the flat metal plate. Finally, the bottom left display shows the time domain waveform received when the flat plate is covered by the absorber. Note the relative attenuation notch seen in the derived frequency display. Also note the characteristic first half cycle, last half cycle time domain response.

For this pulse measurement, the first interesting question that may be posed is whether the absorber has produced the expected response in the time domain. Given the relatively uncomplicated frequency response indicated in Figure K-2, one may postulate that this particular absorber is a relatively simple, single-time-delay type as modeled in Figure K-4. For this type of absorber, there is a front-surface reflection and a delayed back-surface reflection with absorption occurring because of destructive interference between the two reflection paths. A rough check on this particular mechanism can be performed by simply taking the bare metal plate response of Figure K-3 and delaying and adding it to itself to produce the artificial sum waveform shown in Figure K-5. A quick comparison of the waveform actually measured and of the artificial sum shows reasonable good agreement and would seem to confirm that the pulse measurement has given the expected result.

A more precise judgement can be made, however, by generating an equivalent time waveform via point-to-point complex CW measurements. The data shown in Figure K-6 shows CW measurements of the S-band absorber. For this measurement sequence, reflection phase and amplitude with and without the absorber was measured for approximately 400 harmonically related frequency points between 0.045 and 15 GHz. The right display of Figure K-6 shows the relative amplitudes of these frequency measurements (after time windowing to remove multipath nulls). Derived time domain waveforms formed from the individual complex frequency measurements are shown in the left displays, once again for a 1 nsec time window.

Finally, a qualitative comparison can be made in the time domain for the direct pulse and the derived CW measurements, as shown in Figure K-7. Note that, to the first order, the changes between the responses for the bare flat plate and the absorber-covered flat plate are quite similar for both direct pulse and complex CW derived measurements.

As a further check, a similar sequence of measurements was made on the S-band absorber with a quasi X-band illumination waveform. As shown by the data sequences of Figures K-8 through K-10, the S-band absorber produces a small amount of attenuation for the out-of-band waveform and the qualitative comparison of direct pulse and derived CW responses is still reasonably good.

Example #2: An X-Band Absorber

As a further example, the data sequences of Figures K-11 through K-13 and Figures K-14 through K-16 show, respectively, the quasi S-band and quasi X-band responses of a multiple-notch X-band tuned absorber. Note that this absorber is relatively ineffective for the out-of-band illumination and very effective for the designed band of performance. Once again, qualitative comparisons between direct pulse and derived CW responses show good agreement with no surprising differences.

Conclusions

From the comparative measurements performed on twelve microwave absorbers, two general conclusions can be reached:

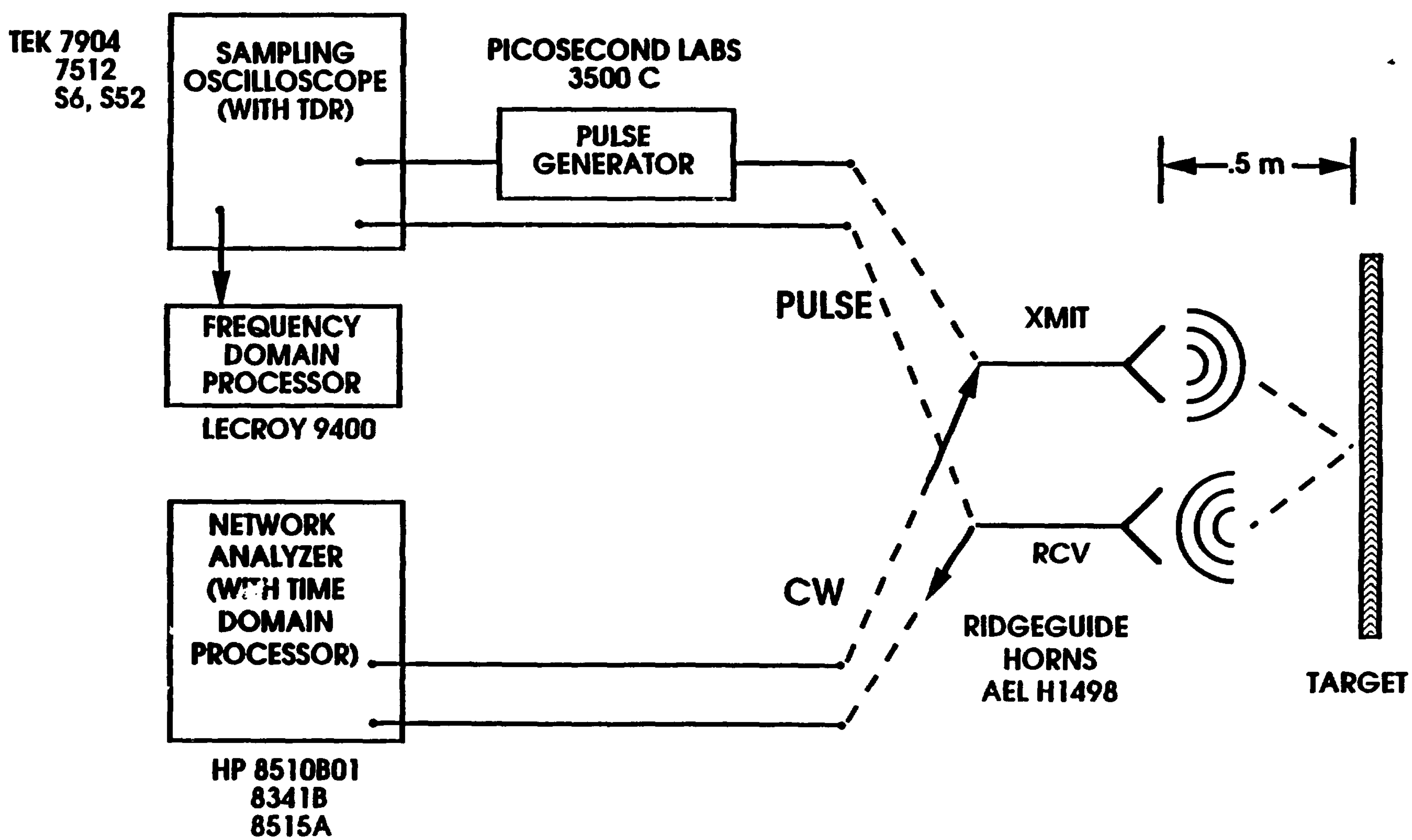
(1) To the first order, both direct pulse and derived CW measurements produce the same results. Therefore, the absorber responses appear to be linear with no hidden hysterisis or energy storage mechanisms.

(2) Swept frequency, CW techniques can be used to derive valid ultra-wideband time domain responses.

It should be noted that all measurements show that, as expected, narrowband absorbers are ineffective against wideband illumination.

FIGURE K-1.

EXPERIMENTAL MEASUREMENT FACILITY



(SAME ANTENNAS, CABLES, TARGET FOR EACH TYPE OF MEASUREMENT)

FIGURE K-2.

ABSORBER POWER RESPONSE OF A TYPICAL S-BAND TUNED ABSORBER

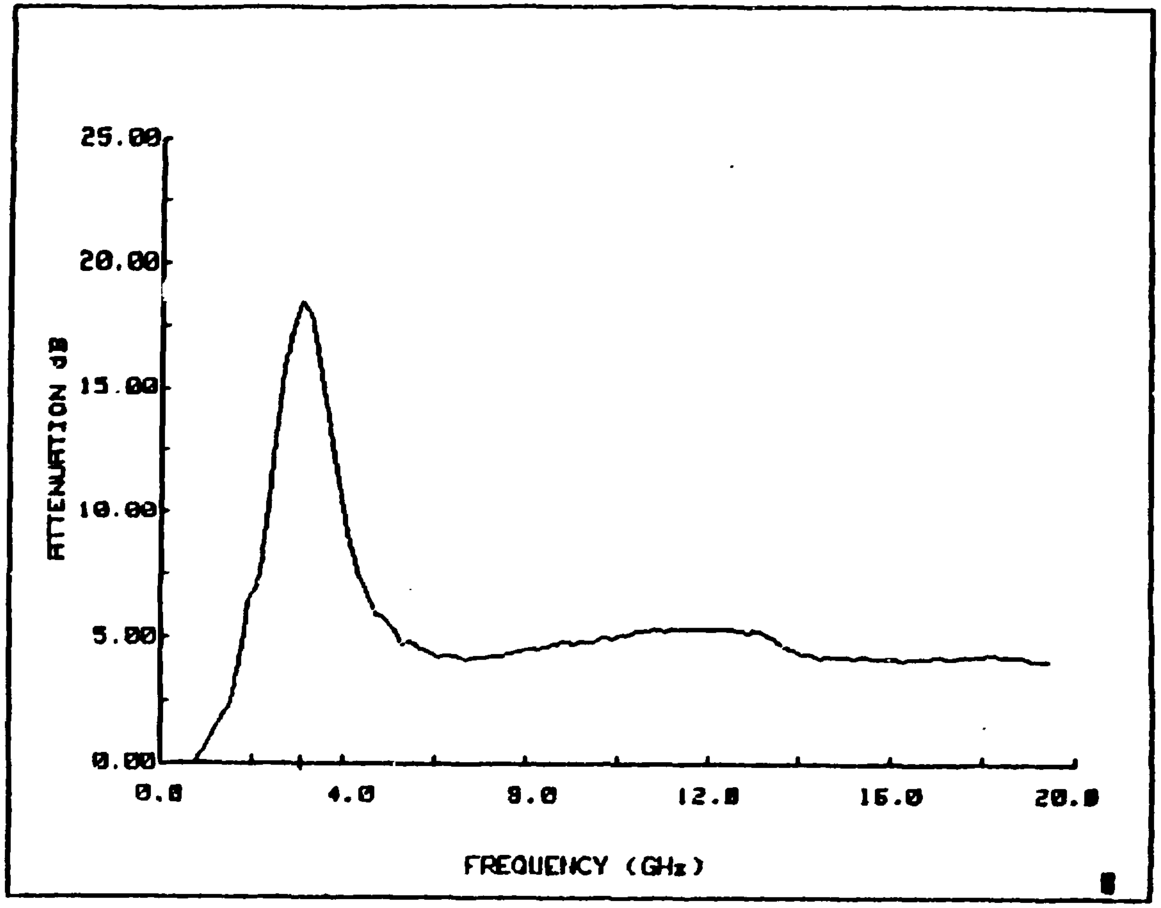


FIGURE K-3. **SHORT PULSE MEASUREMENT OF ABSORBER**

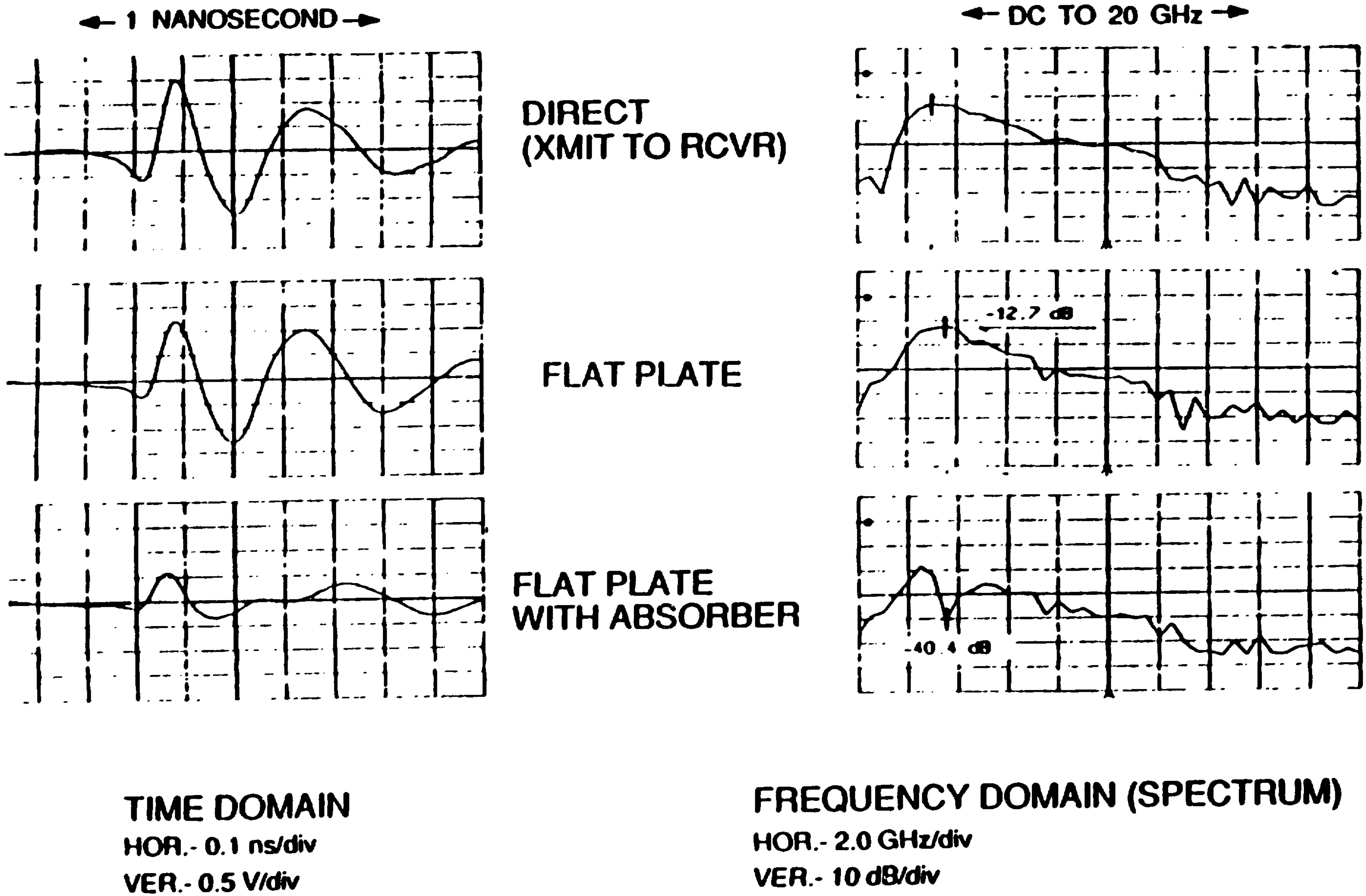
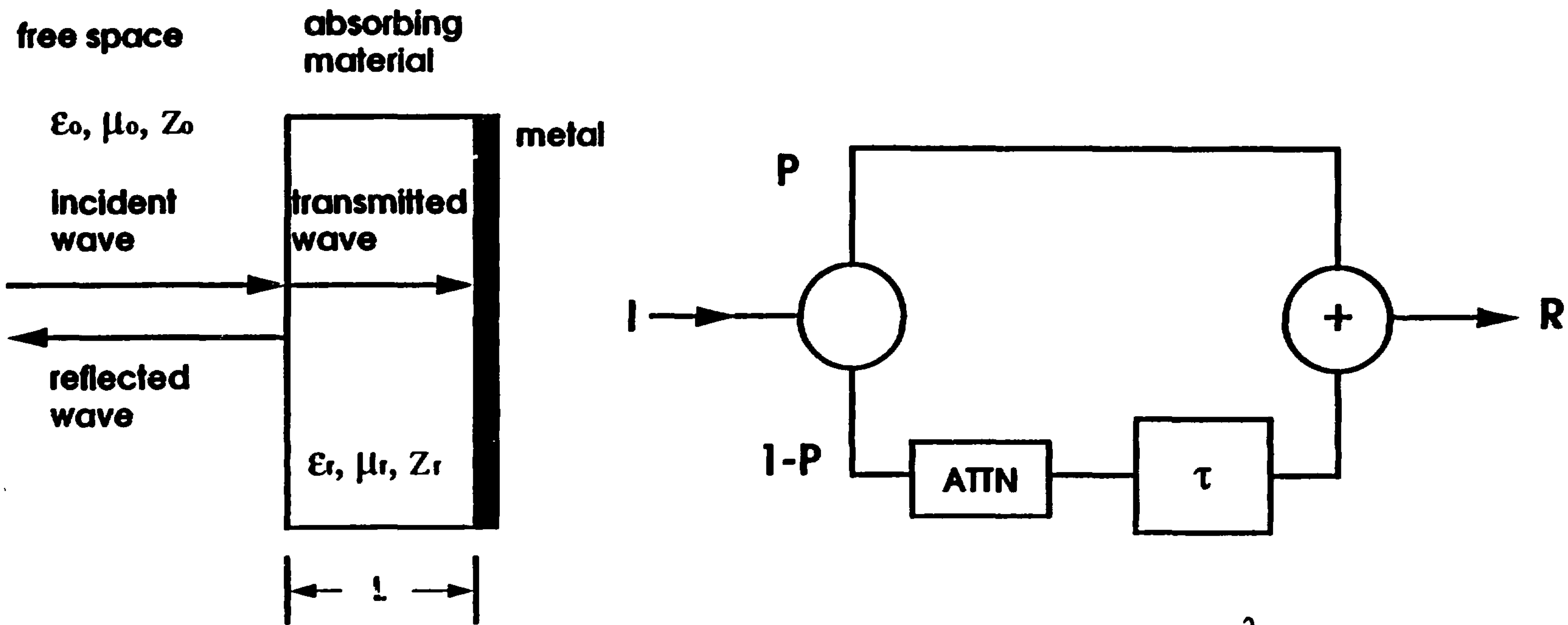


FIGURE K-4.

ABSORBER MODEL



$$\tau = \frac{\lambda}{2}$$

FIGURE K-5. INTERPRETATION OF ABSORBER MEASUREMENT IN TIME DOMAIN

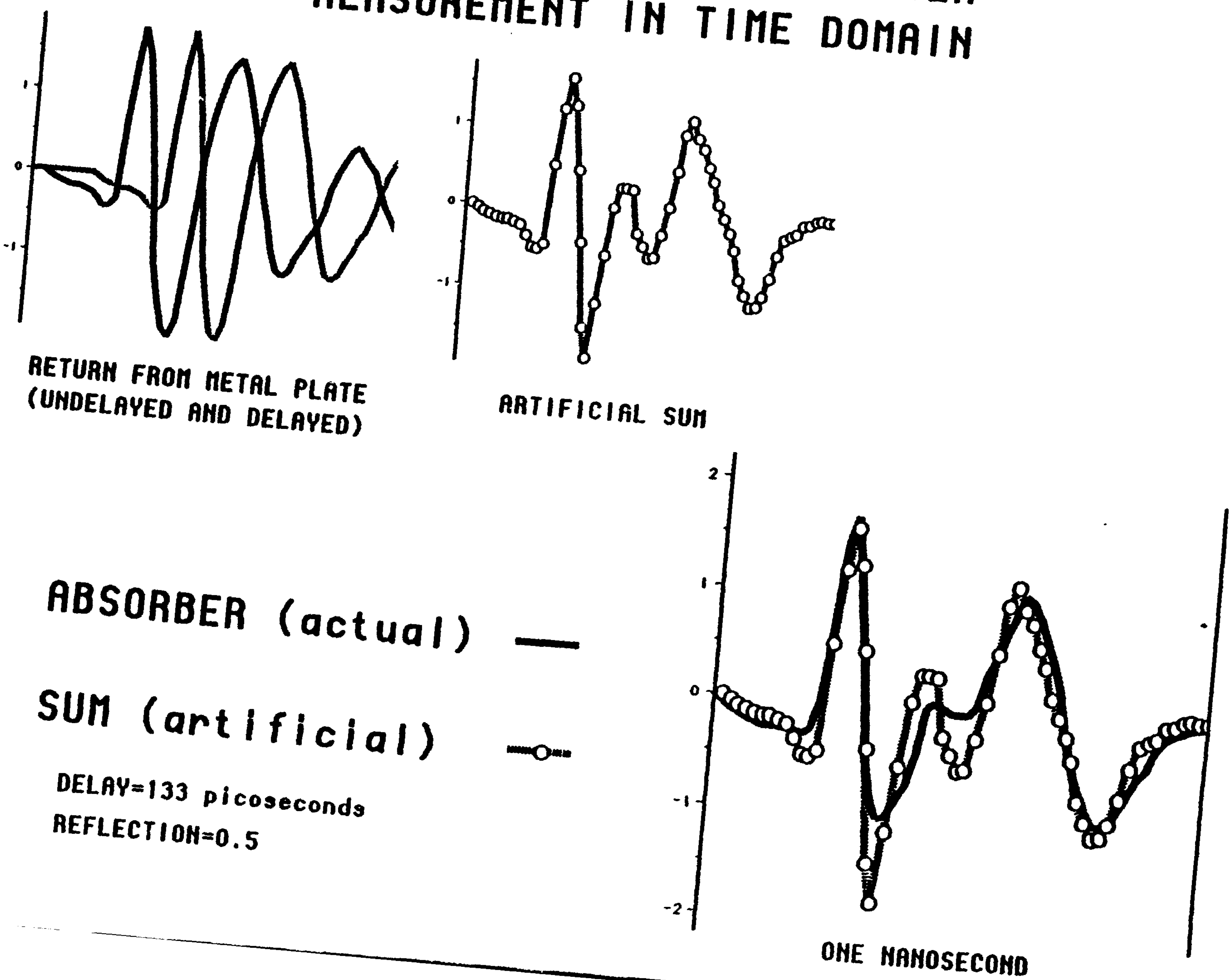
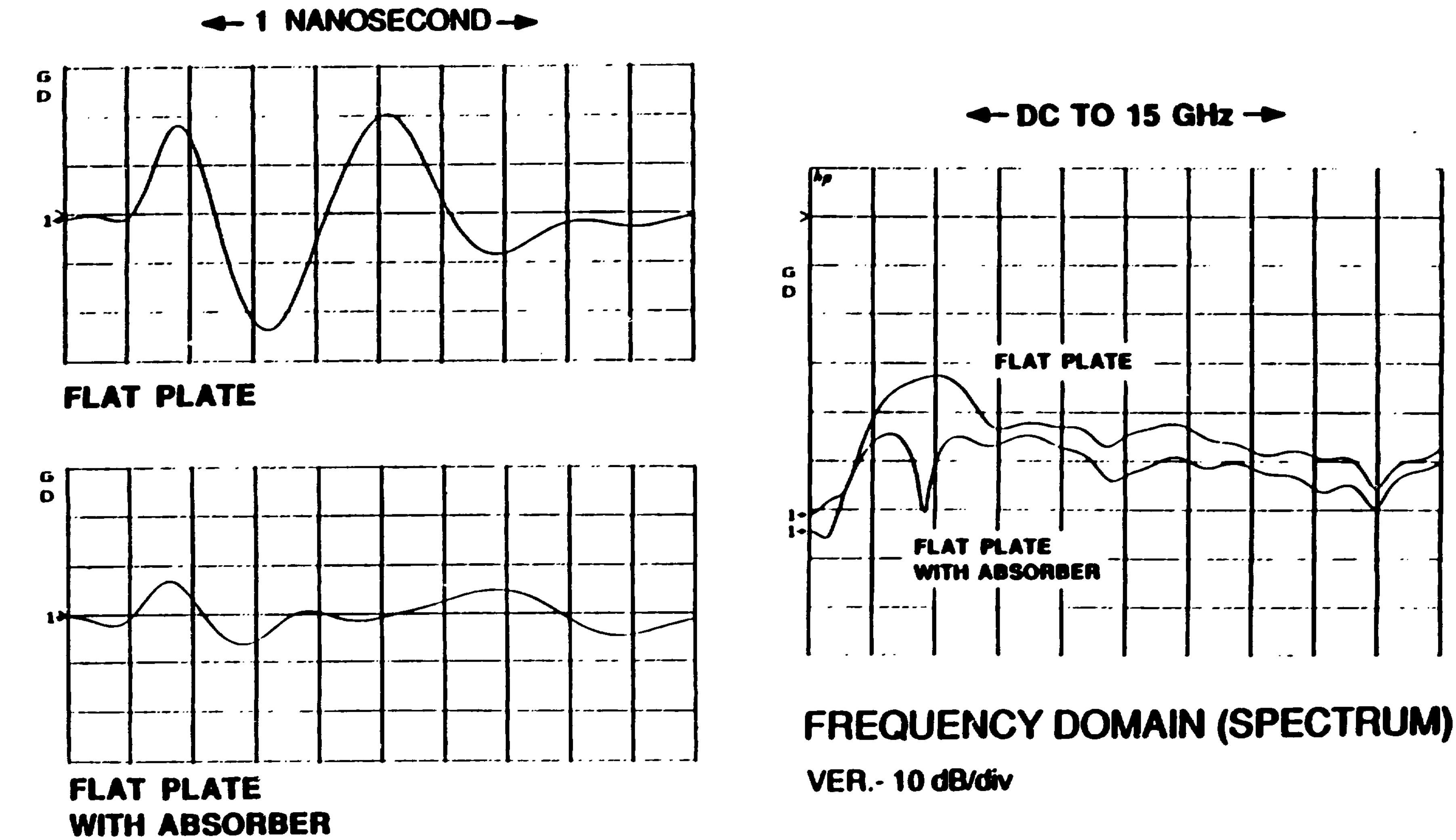


FIGURE K-6.

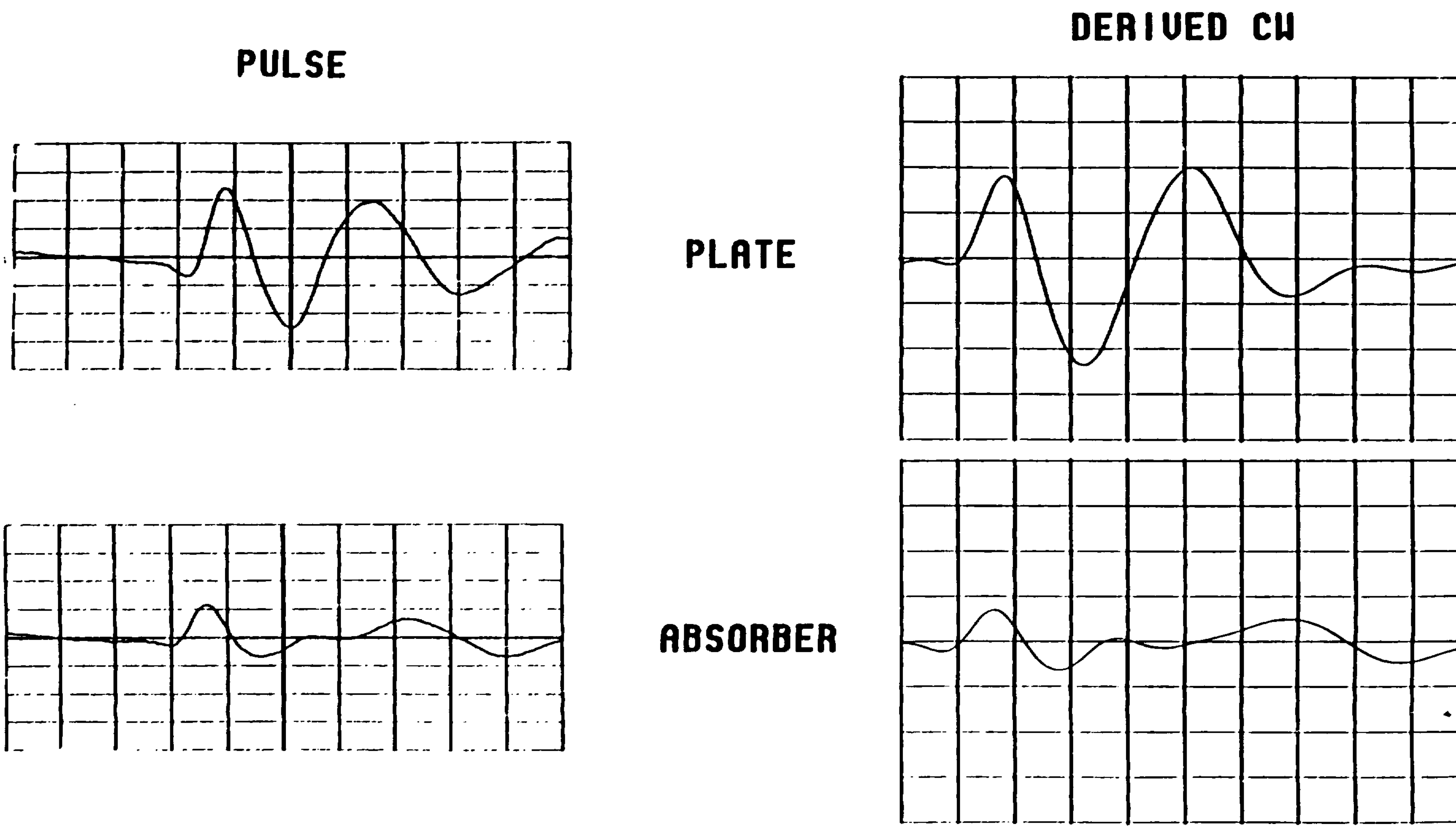
CW (8510B) MEASUREMENT OF ABSORBER



TIME DOMAIN
HOR.- 0.1 ns/div

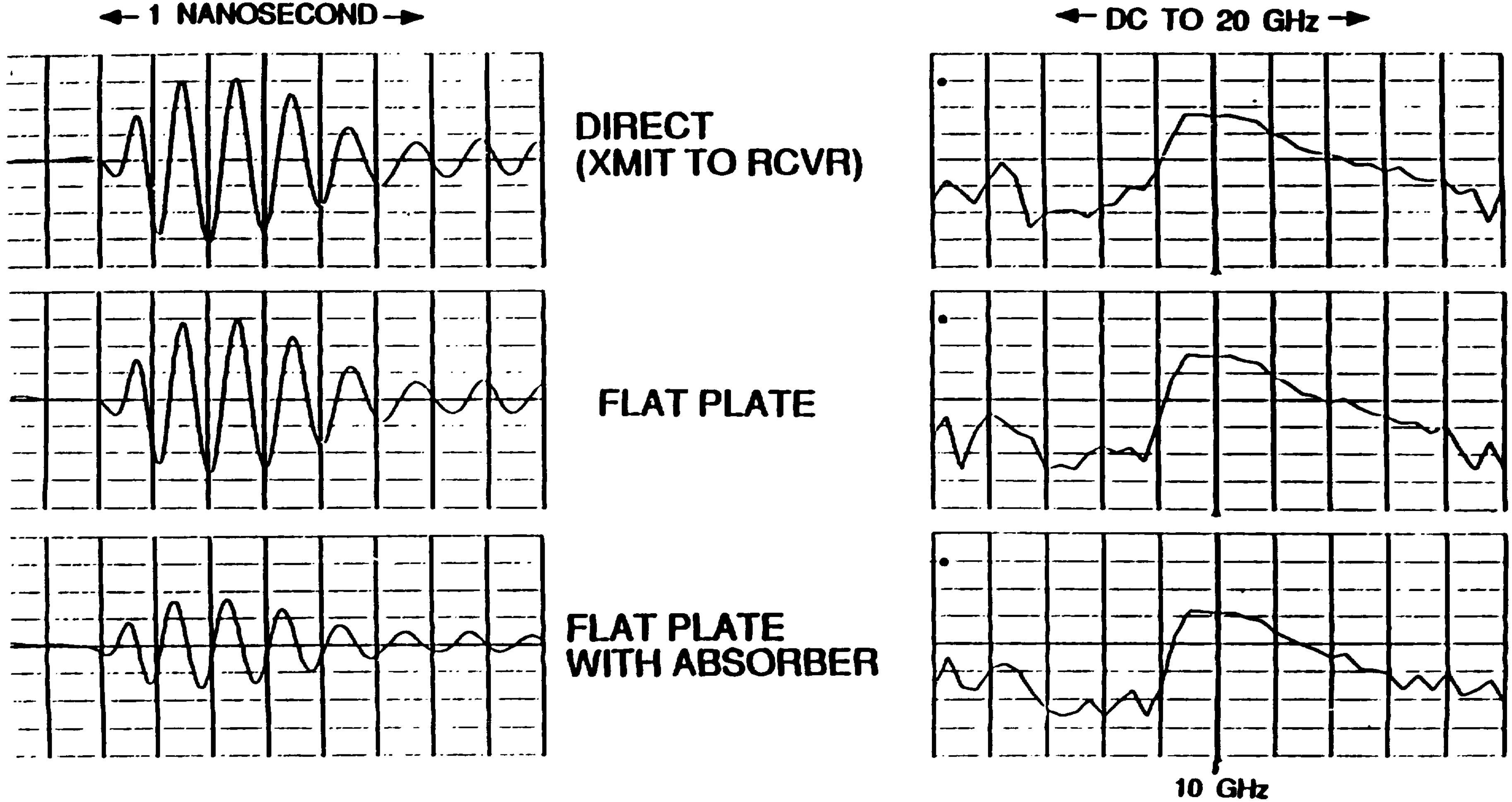
FREQUENCY DOMAIN (SPECTRUM)
VER.- 10 dB/div

FIGURE K-7. COMPARISON OF DIRECT PULSE AND DERIVED CW TIME DOMAIN RESPONSES



One Nanosecond Window

FIGURE K-8. SHORT PULSE MEASUREMENT OF ABSORBER

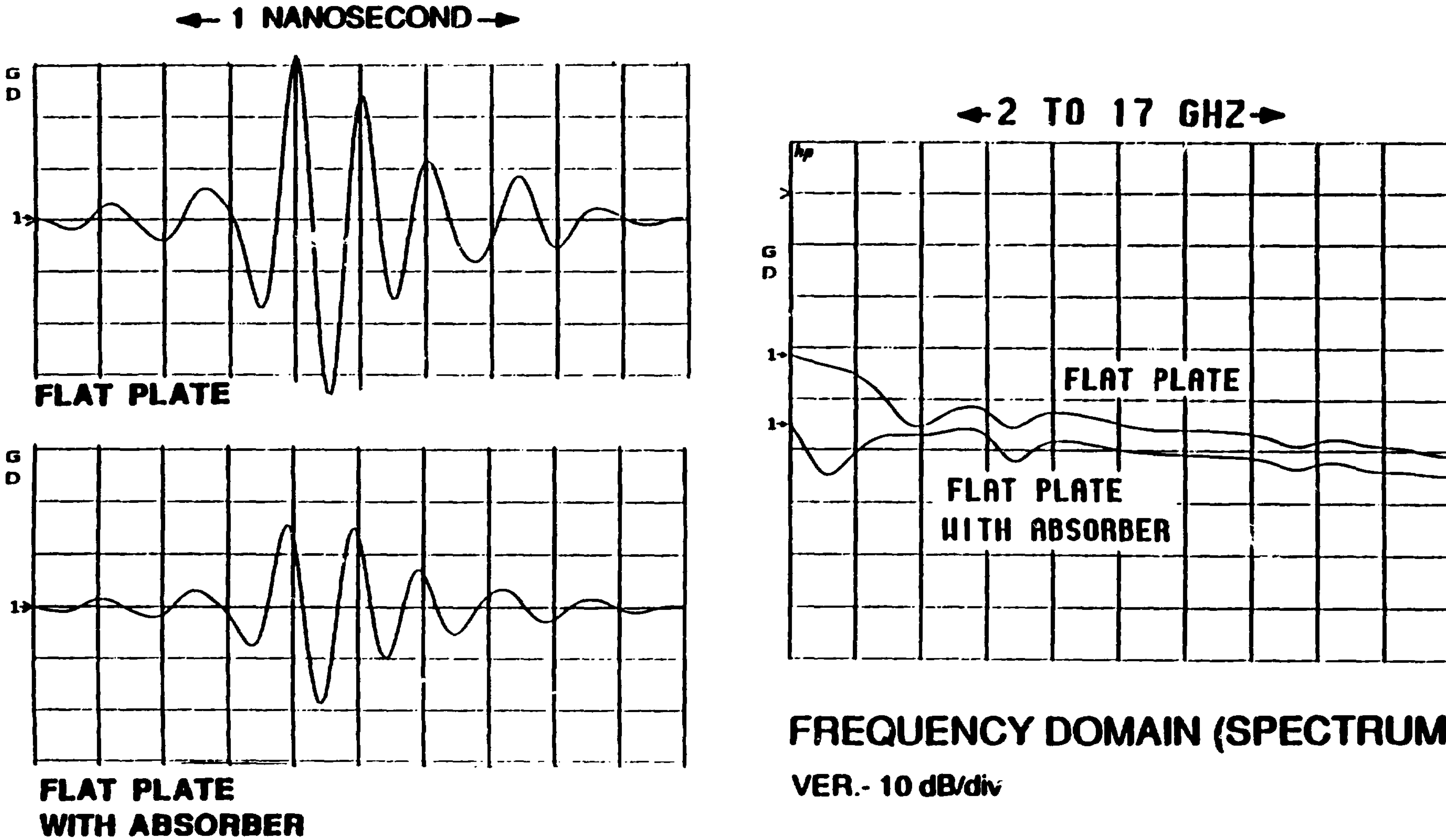


TIME DOMAIN
HOR.- 0.1 ns/div
VER.- 0.5 V/div

FREQUENCY DOMAIN (SPECTRUM
HOR.- 2.0 GHz/div
VER.- 10 dB/div

FIGURE K-9.

CW (8510B) MEASUREMENT OF ABSORBER



TIME DOMAIN
HOR.- 0.1 ns/div

FREQUENCY DOMAIN (SPECTRUM)
VER.- 10 dB/div

FIGURE K-10. COMPARISON OF DIRECT PULSE AND DERIVED CW TIME DOMAIN RESPONSES

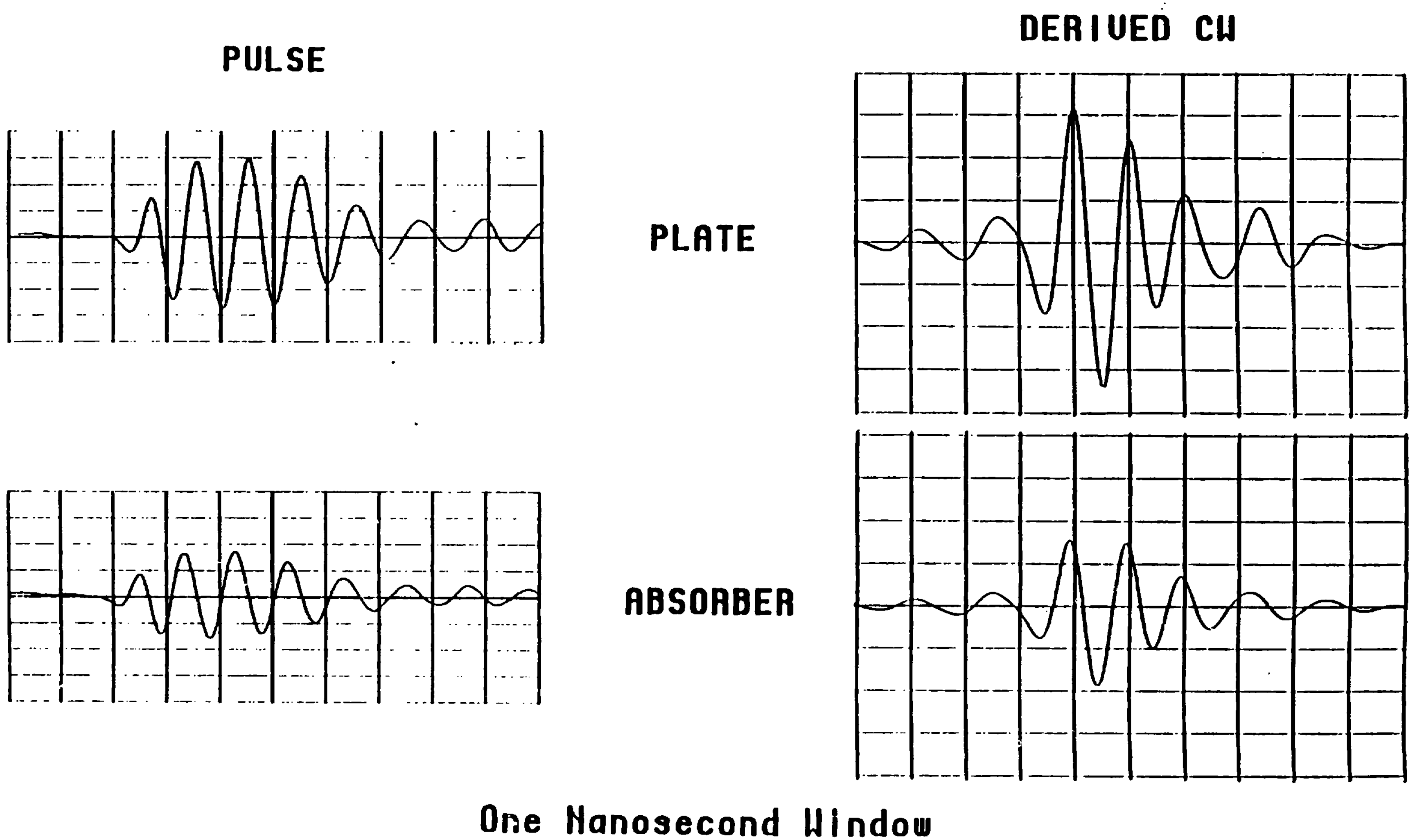


FIGURE K-11. SHORT PULSE MEASUREMENT OF ABSORBER

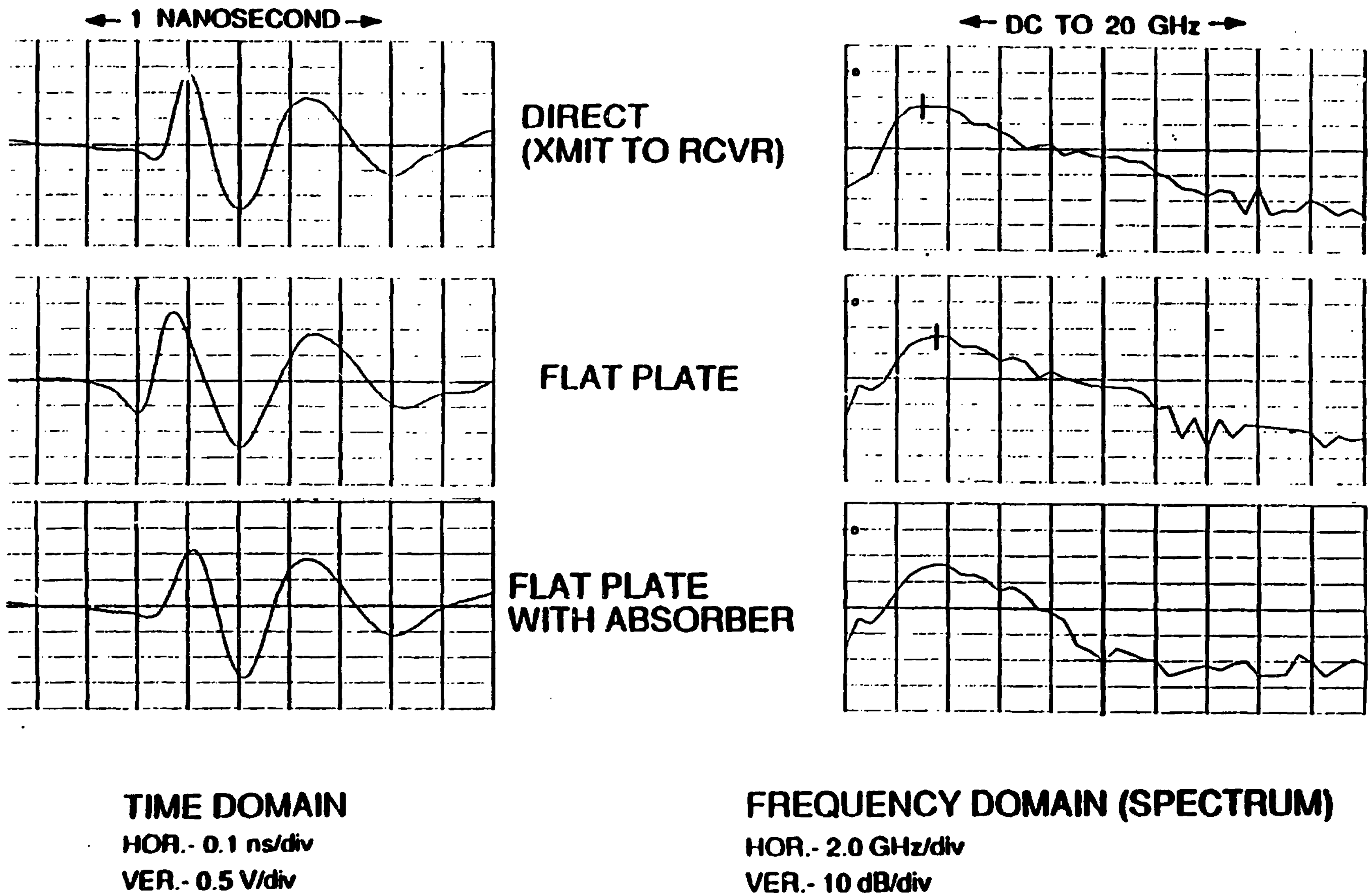
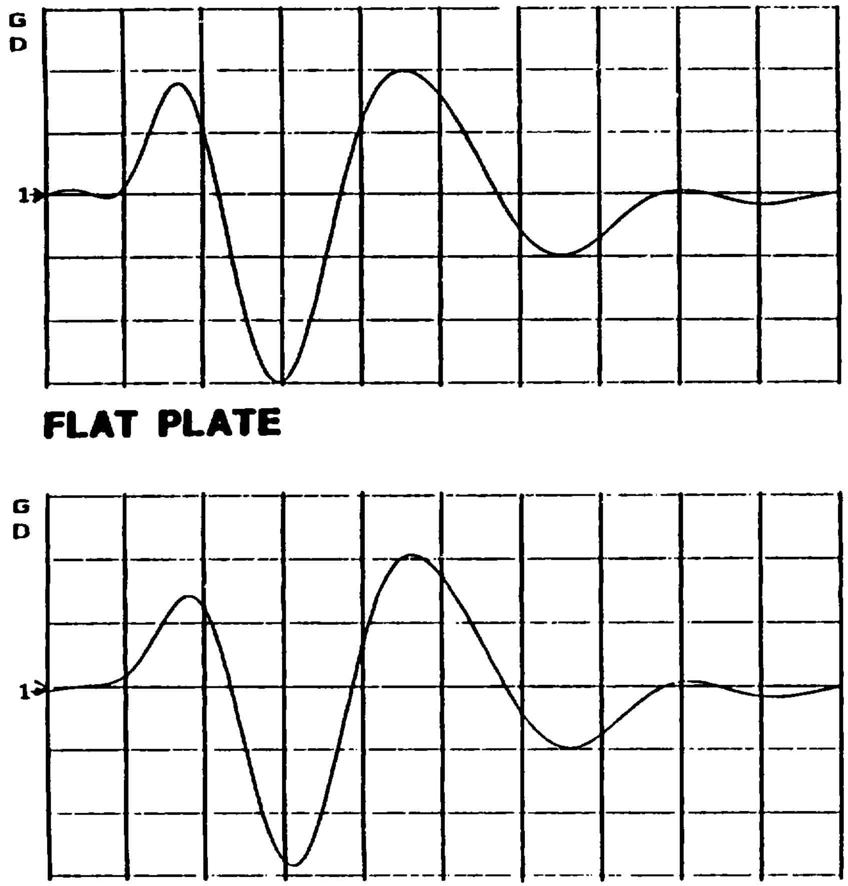


FIGURE K-12.

CW (8510B) MEASUREMENT OF ABSORBER

← 1 NANOSECOND →

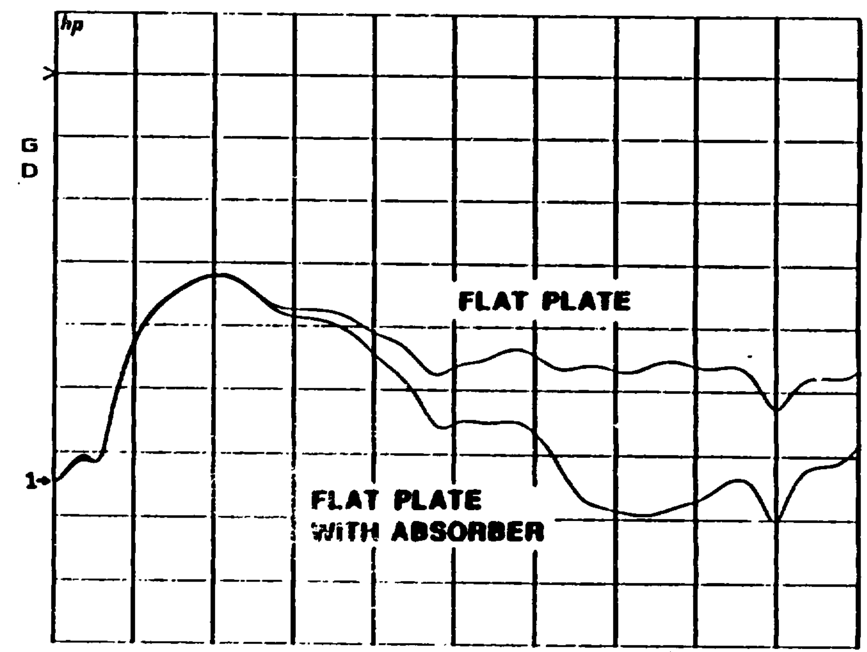


FLAT PLATE

FLAT PLATE
WITH ABSORBER

TIME DOMAIN
HOR.- 0.1 ns/div

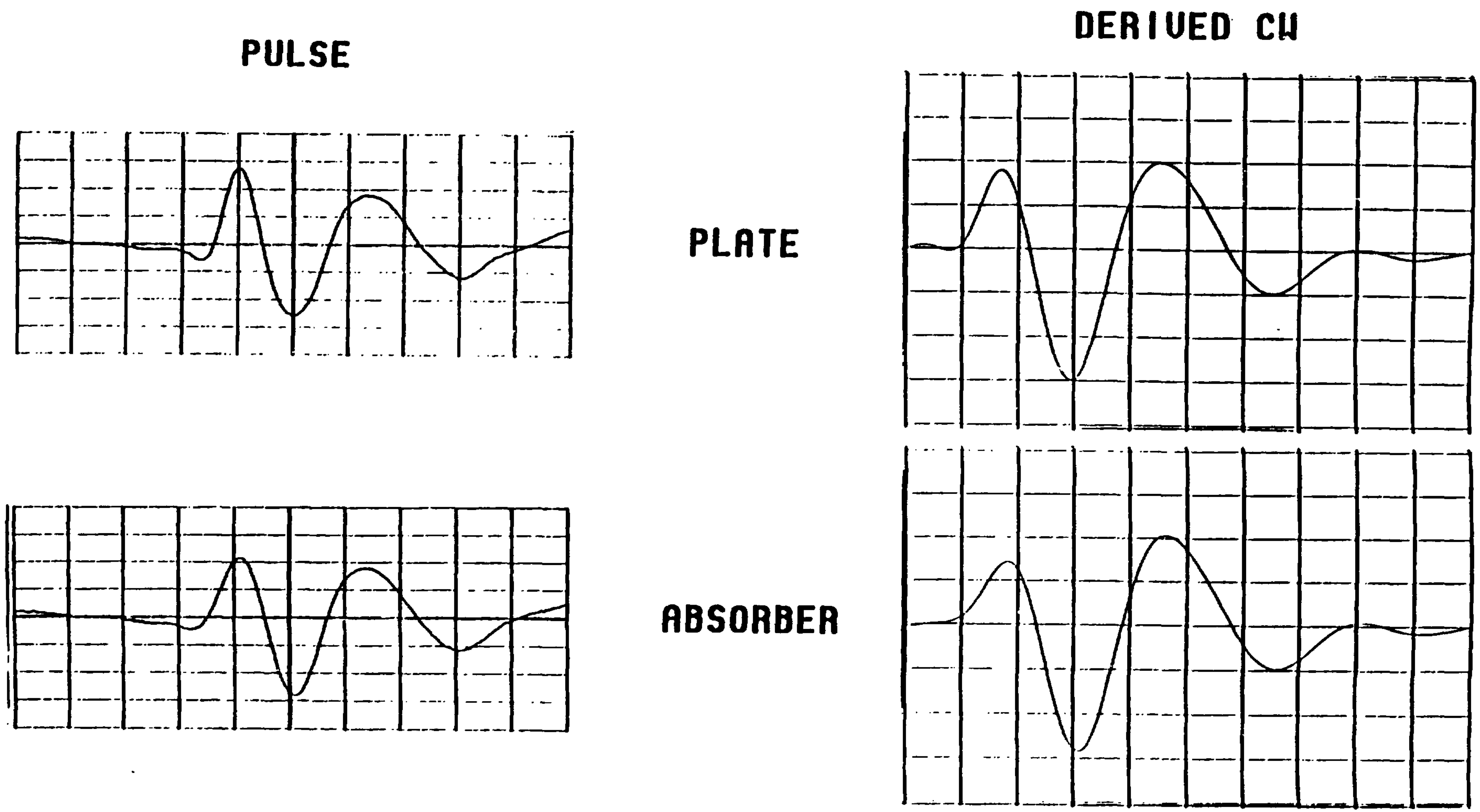
← DC TO 15 GHz →



FREQUENCY DOMAIN (SPECTRUM)
VER.- 10 dB/div

FIGURE K-13.

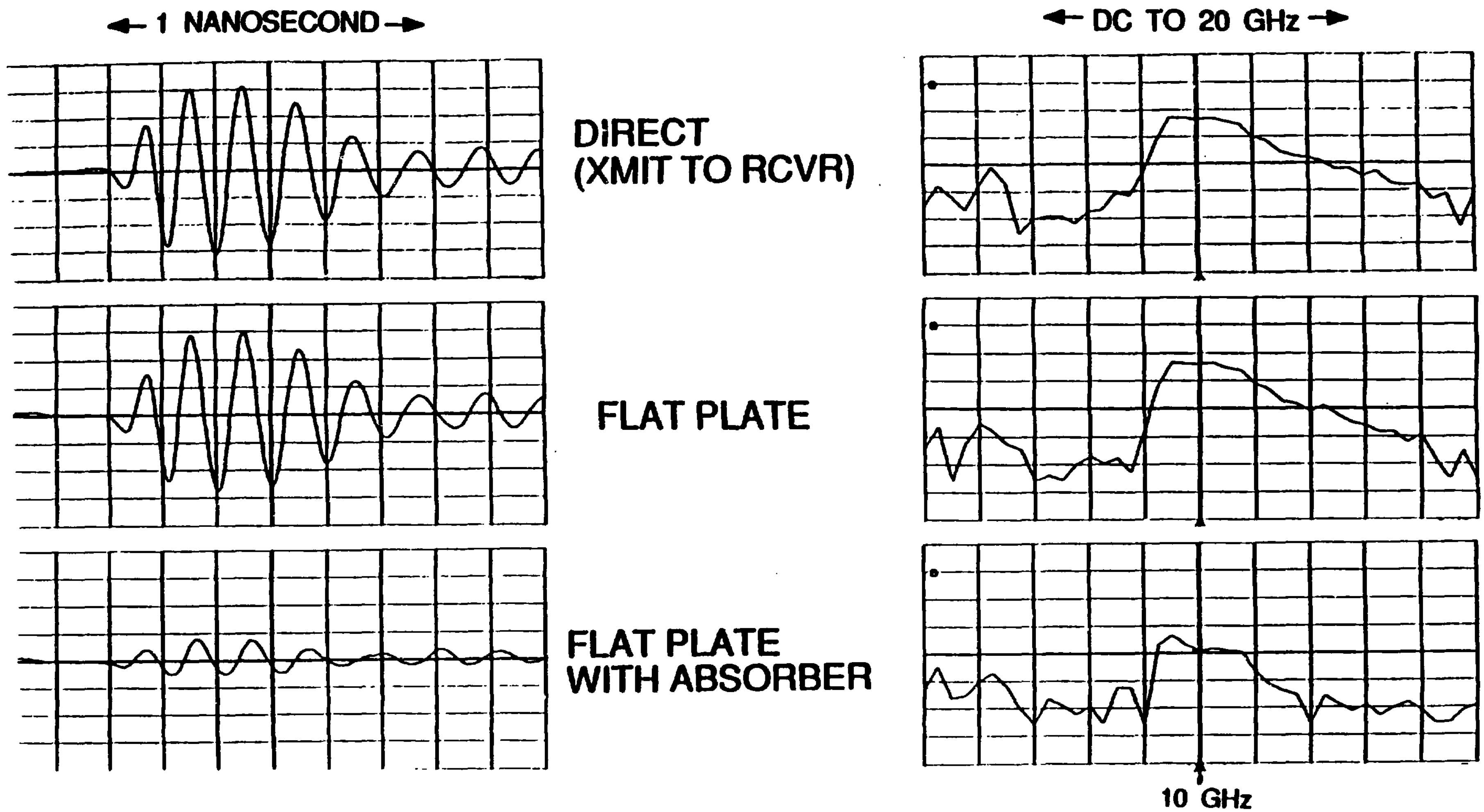
COMPARISON OF DIRECT PULSE AND DERIVED CW TIME DOMAIN RESPONSES



One Nanosecond Window

FIGURE K-14.

SHORT PULSE MEASUREMENT OF ABSORBER

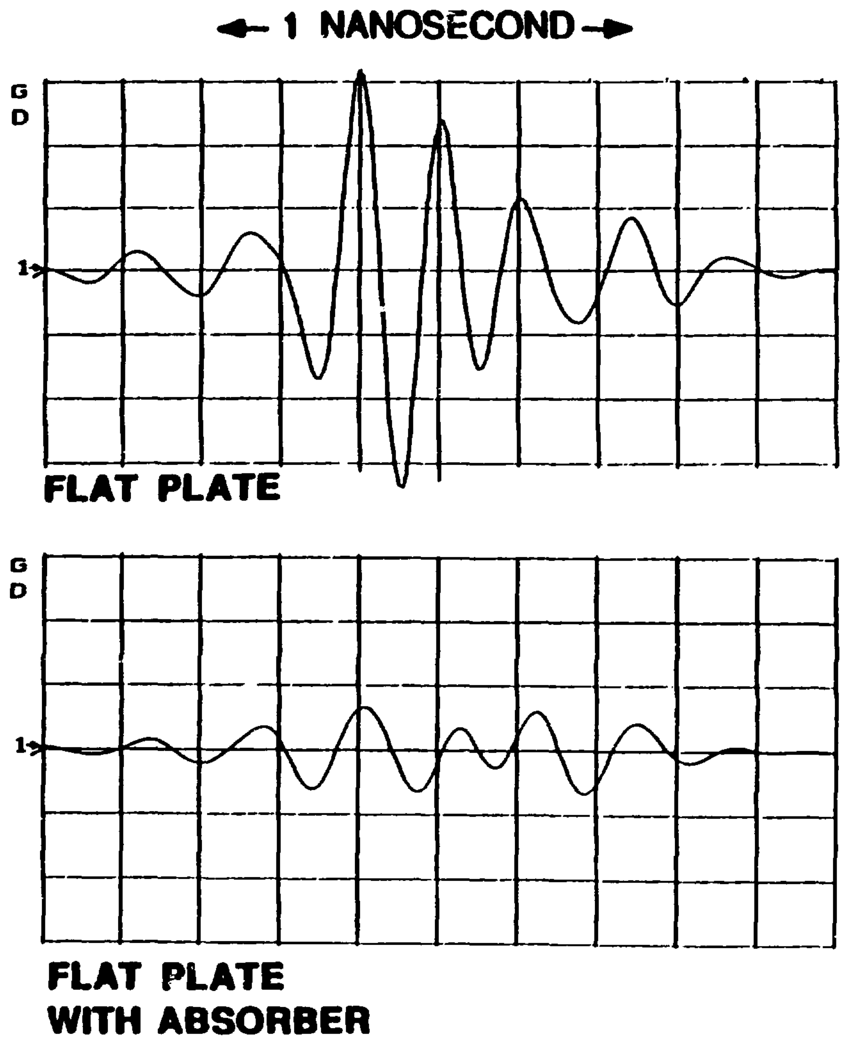


TIME DOMAIN
HOR.- 0.1 ns/div
VER.- 0.5 V/div

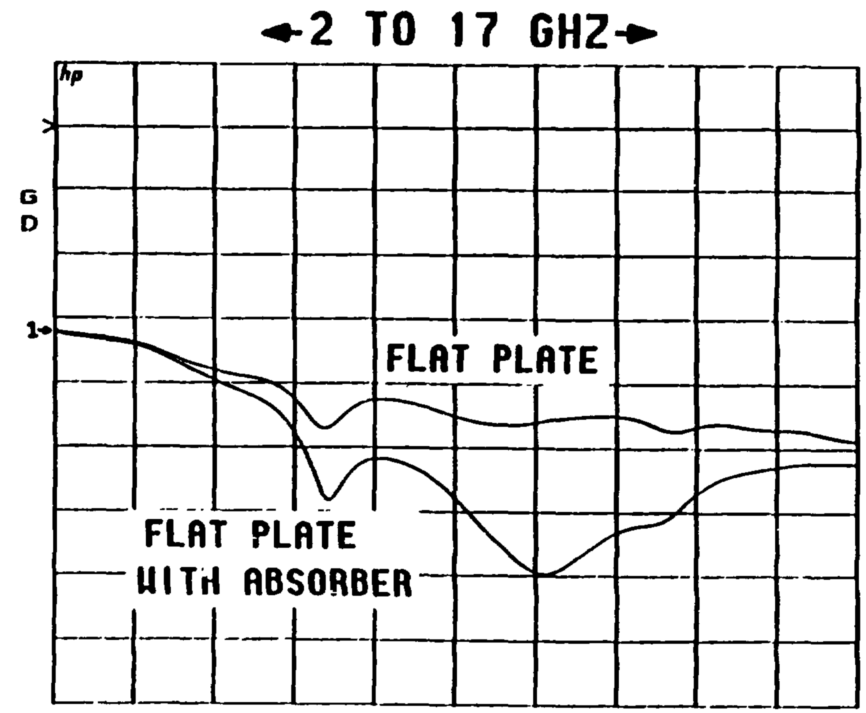
FREQUENCY DOMAIN (SPECTRUM)
HOR.- 2.0 GHz/div
VER.- 10 dB/div

FIGURE K-15.

CW (8510B) MEASUREMENT OF ABSORBER



TIME DOMAIN
HOR.- 0.1 ns/div



FREQUENCY DOMAIN (SPECTRUM)
VER.- 10 dB/div

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
3701 NORTH FAIRFAX DRIVE
ARLINGTON, VA 22203-1714

Recd
6/13/2001

June 11, 2001

MEMORANDUM FOR XENA ROGERS, DTIC ACQUISITIONS BRANCH

SUBJECT: Request Change in Distribution Statement for AD B146160, "Assessment of Ultra Wideband (UWB) Technology"

This memorandum is to request that the distribution statement for **AD B146160**, "Assessment of Ultra Wideband (UWB) Technology," be changed to "Distribution A, Approved for public release; distribution is unlimited."

Please let me know if you have questions on this request. I can be reached at (703) 526-4163 or damick@darpa.mil. Thank you for your help.

Debra K. Amick
Technical Information Officer